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MARTIN MARIETTA

Cooling Season Performance of an Earth-Sheltered Office/Dormitory Building in Oak Ridge, Tennessee

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COOLING SEASON PERFORMANCE OF AN EARTH-SHELTERED OFFICE/DORMITORY BUILDING IN OAK RIDGE, TENNESSEE

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ABSTRACT

Detailed hourly measurements taken in and around an underground office-dormitory building for two summers document energy savings; whole building-component interface problems; and specific cooling contributions from earth contact, interior thermal mass, and an economizer. The Joint Institute Dormitory (JID) saves about 30% compared with well-built above-grade buildings in a climate typical of Oak Ridge, Tennessee, and has the potential to save as much as 50%. The detailed measurements, which include extensive thermal comfort data, indicate that at least 90% of the occupants are comfortable all of the time. The thermal performance measurements and analysis determine that the peak cooling requirement of this building is 50% less than that of well-built above-grade structures, permitting a cost savings on installed cooling capacity. The dominant building components contributing to the good thermal performance are the structural thermal mass, the earth-covered roof, and the earth contact provided by the bermed walls and slab floor. The 372-m^2 (4000 gross ft^2) building used about $300 (at 5.7 ¢/kWh) to cool and ventilate from May through September.

Eliminating a number of building design and construction anomalies could improve the whole-building performance and reduce the seasonal cooling cost another $85. Close examination of the thermal performance of this building revealed that a very efficient heat pump and thermally sound envelope do not necessarily produce optimum performance without careful attention given to component interface details.

1. INTRODUCTION

The cooling season thermal performance of a 372-m^2 (4000 gross ft^2) energy-efficient, earth-sheltered building, the Joint Institute Dormitory (JID), in Oak Ridge, Tennessee, was closely monitored through the 1982 and 1983 summer months. This building is used for office and dormitory space at the Oak Ridge National Laboratory (ORNL). The entire inside space is conditioned around the clock.

The purpose of this field monitoring and analysis project is to advise architects, engineers, and building owners on the actual field performance of a variety of design concepts that can contribute to more comfortable energy-efficient small commercial and residential structures. These concepts include earth-covered roof, bermed walls, insulated concrete slab floor, structural thermal mass directly coupled with the interior space, and an economizer for nighttime cooling when ambient conditions are acceptable. Because this report focuses on energy use in the cooling season, life-cycle cost analysis is not provided. A heating season thermal performance analysis on this building can be found in ref. 1, and a full seasonal analysis will be available shortly. A floor plan, building cross section, and photograph are shown in Fig. 1.1. The building's roof, north wall, and part of the east wall are earth covered. Fire code restrictions required exits on both the east and west ends of the building, preventing the building from being fully bermed on three sides.

The whole building saves about 30% of the energy used during both the heating and cooling seasons compared with a DOE-2.1A building simulation model using identical weather parameters and a well-built, above-grade structure with identical interior usage patterns and ventilation air change as the JID.[1,2] The above-grade building model used for comparison has metric R values (RSIs) of 4.6 $h \cdot m^2 \cdot {}^\circ C/W$ (R = 26 $h \cdot ft^2 \cdot {}^\circ F/Btu$) for the roof and 2.5 $h \cdot m^2 \cdot {}^\circ C/W$ (R = 14 $h \cdot ft^2 \cdot {}^\circ F/Btu$) for the walls. It has the same total glass area, but the glass is redistributed with 50% of the total glass on both the north and south sides; the overhang on the south side is 0.6 m (2 ft) instead of 1 m (3.5 ft).

A second comparison of the JID cooling season performance was made with an actual well-built, energy-efficient, above-grade building exposed to the same 1982 meteorological conditions. The results of this comparison show that 30% energy savings during the cooling season over efficient, above-grade structures is a reasonable estimate for a climate such as that in Oak Ridge.

The building used for this comparison is the TECH House III, located at the Tennessee Energy Conservation in Housing (TECH) Complex in Knoxville, Tennessee, approximately 25 miles from the JID site.[3] This structure is a well-insulated house with 167 m^2 (1800 ft^2) of gross floor area, walls with an RSI of 3.9 (R = 22), a cathedral ceiling with an RSI of 3.9 (R = 22), a flat ceiling with an RSI of 7.4 (R = 42), floors with an RSI of 3.9 (R = 22), and double-glazed windows. This unoccupied building is very carefully monitored for ongoing heat pump field testing; its interior electric usage is approximately the same per unit floor

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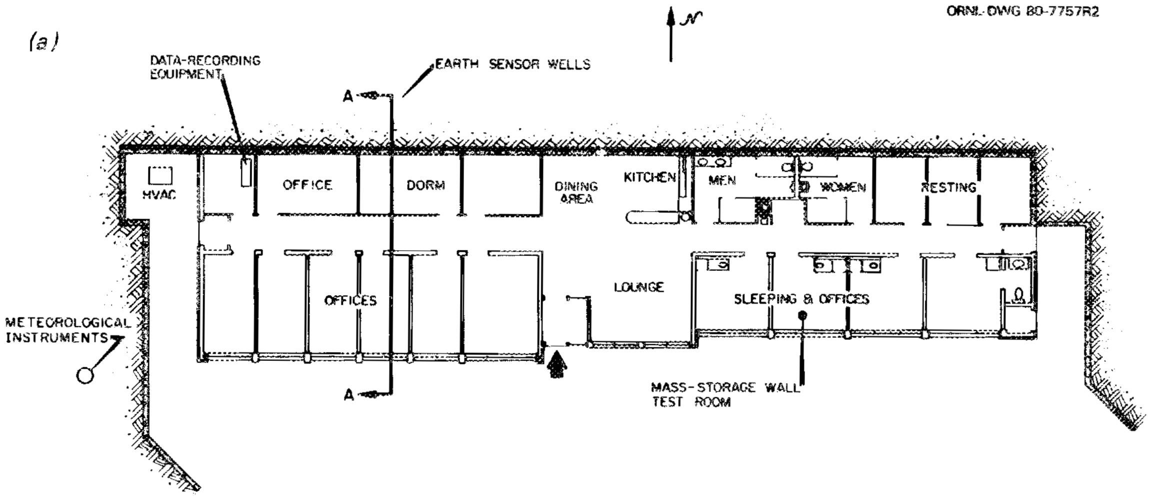

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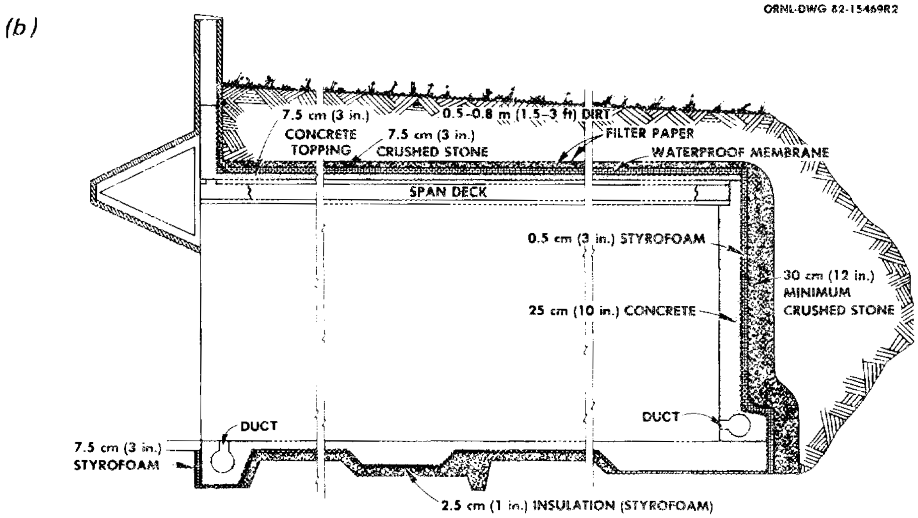

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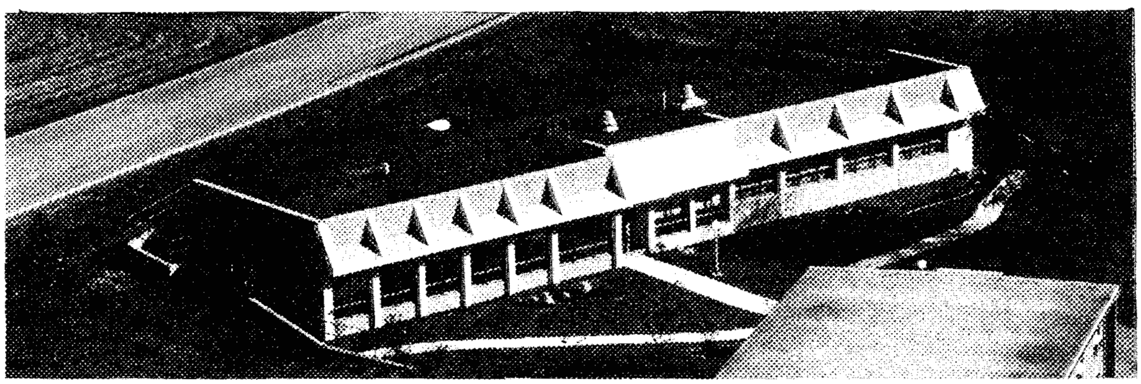

Fig. 1.1. Joint Institute Office and Dormitory: *(a)* floor plan, *(b)* cross section, and *(c)* photograph.

area as that of the JID. A third comparison with a small office building located near the JID suggests that the JID uses 5–30% less energy for cooling after normalizing for internal occupancy behavior. However, these offices are conditioned only 30% of the time.

The JID's south-facing wall, designed primarily for direct solar gain in the heating season, consists of 75% glass area. South-facing glass area amounts to 19% of the floor area in the building. To prevent direct solar gain in the summer, a 1-m (3.5-ft) extended overhang on the south side shades the windows from May to mid-August. However, even without direct solar gain during the summer, south-facing windows transmit significant heat gain because of ground reflectance, sky radiation, and temperature differences between inside and outside air. The total heat gain from these south-facing windows amounts to about 40% of the daily sensible cooling requirement.

In a number of passive solar buildings, incorporating principles designed to optimize heating season performance has resulted in summertime overheating. For the 1982 and 1983 summer months the JID was not permitted to overheat. The thermal mass in and around the building is sufficient to absorb diurnal heat spikes, keeping the occupied space thermally acceptable at all times to at least 90% of the people.

The mechanical package in the building has a maximum total cooling capacity at 35°C (95°F) of only 10.5 kW (36,000 Btu/h) or 28 W/m^2 [9 $Btu/(h \cdot ft^2)$] of gross floor area. More conventional well-built, above-grade structures in the same region with the same floor area have three times the cooling capacity of this building. The peak hourly power requirement for mechanical cooling is 4.3 W/m^2 [1.3 $Btu/(h \cdot ft^2)$] of floor area. Another salient feature of this type of building, in addition to annual energy savings, is the reduction in summertime peak electric load by a factor of two or three with no effect on occupant thermal comfort.

2. DESCRIPTION

2.1 THE CLIMATE

The climate surrounding this building in the summer is normally hot and humid. In 1982, June, July, and August provided an average maximum air temperature of 29°C (85°F), diurnal swings of 8°C (15°F), and mean daily temperatures of 24°C (76°F). The average relative humidity varied from 92% at 4:00 a.m. to 65% at 4:00 p.m. There were a total of 500 cooling degree-days (DD) at 18°C (900 DD base 65°F), which is typical for the area.

The 1983 summer, on the other hand, started with below normal daily air temperatures in June, averaging 22°C (71.5°F), and ended with record-breaking high temperatures [~38°C (~100°F)] in July and August. Temperatures averaged 26°C (78°F) in July and August, with average daily maximums of 33°C (91°F) and diurnal swings of 13°C (24°F). In contrast, the peak temperature in August 1982 never rose above the average diurnal maximum in August 1983. The cooling DD for June, July, and August 1983 totaled 590 DD base 18°C (1061 DD base 65°F).

2.2 THE BUILDING

2.2.1 Architectural Features

The building contains 345 m^2 of floor space used for offices, dormitory rooms, and a lounge and dining room area. The north wall and part of the east wall are earth bermed and planted with grass and small shrubs. The earth provides a number of desirable features: visual screen of other buildings from the nearby highway leading to the main entrance of ORNL, a sound barrier completely blocking the noise from automobiles and trucks traveling at highway speeds less than 11 m (35 ft) away, thermal mass providing a heat sink during the early summer months, and shelter from direct solar insolation. The earth also supports vegetation that transpires and helps to offset the net radiative gain to the roof and sometimes contributes an element of sensible cooling to the building.

The building envelope consists primarily of poured concrete and masonry construction, as shown by the building cross section in Fig. 1.1(*b*). All walls have 7.5 cm (3 in.) of polystyrene foam board insulation fastened to the outside of the building. The bermed walls are faced with sloping earth, and the exposed walls are covered with an epoxy system that looks like stucco. The roof consists of precast concrete sections covered by 5 to 7 cm (2 to 3 in.) of poured concrete to provide a smooth adhesive surface for a waterproof membrane. The membrane is covered by 7.5 cm (3 in.) of extruded polystyrene insulation, a full 7.5-cm (3-in.) French drain in the form of a gravel seam, filter paper, and earth sloping from 0.76 to 0.46 m (2.5 to 1.5 ft).

2.2.2 Mechanical Equipment

The heat pump indoor blower operates continuously, preventing air stagnation, aiding thermal mixing, and introducing a steady-state level of background noise. Supply air ducts are located within the wall footings to enhance the coupling between the building air and effective thermal mass in the envelope. Most of the exhaust air is vented through two fan ports in the roof, one in the restrooms and a second in the kitchen. Repetitive air exchange measurements using tracer gas techniques indicate that the air change rate varies from 0.4 air changes per hour with no exhaust fan operation to 0.7 air changes per hour with one fan and 1.2 with both exhaust fans operating. The exhaust fan operation is checked every minute, and the calculated operating time is recorded each hour.

The three entrances to this building are through vestibules. Results from the tracer gas air change rate tests show no significant differences in air change rate as a function of door openings. However, with the inside vestibule door open, the air change rate increased a maximum of 0.08 per hour for every door opening. This increase in air exchange rate also varied with wind speed and direction. The vestibule doors are normally closed at all times, so the variable traffic rate into and out of the building should not alter the assumption that air exchange in the building is ventilating fan-dominated.

A manufacturer's nominally rated 12.3-kW (3.5-ton at 95°F) heat pump and enthalpy-controlled economizer provide space cooling to this building. The measured cooling output of the installed heat pump unit was about 20% below rated capacity; however, this was apparently caused by application problems (as described in Sect. 4.2) and was not the fault of the mechanical package. The economizer control is set to bring in ambient cooling only when the outside air enthalpy is below the inside air enthalpy. Since the building circulating fan runs continuously, during those times when the outside air enthalpy is less than the inside air enthalpy the economizer cycle essentially increases the air change rate to about 4 per hour, providing additional cooling with no additional electric energy expenditure.

3. THERMAL COMFORT MEASUREMENTS

The thermal performance of a building is determined not only by the envelope coupled with the heating, ventilating, and cooling (HVAC) system and its controls, but also the building operation. This building is kept within the prescribed thermal comfort range, shown in Fig. 3.1, during the cooling season. The predicted mean vote (PMV) scale is an index that predicts the mean value of the subjective ratings of a large group of people on a seven-point thermal sensation scale ranging from −3 (cold) to +3 (hot). The subjective and physiological reaction of a person to the thermal environment is determined by the rates of a person's heat generation and heat emission, which in turn are functions of six parameters: air temperature, mean radiant temperature, air velocity, humidity, the individual's metabolic rate, and the thermal insulation of clothing. When any combination of these factors satisfies the comfort equation derived by Professor P. O. Fanger, most people will feel thermally comfortable. People who are thermally neutral do not know whether they would like to be warmer or cooler.[4]

All the comfort factors can be measured and used to predict people's subjective response to any given combination of environment, clothing, and activity level. These reactions follow a normal distribution about a mean which is termed the PMV. The PMV in the building was

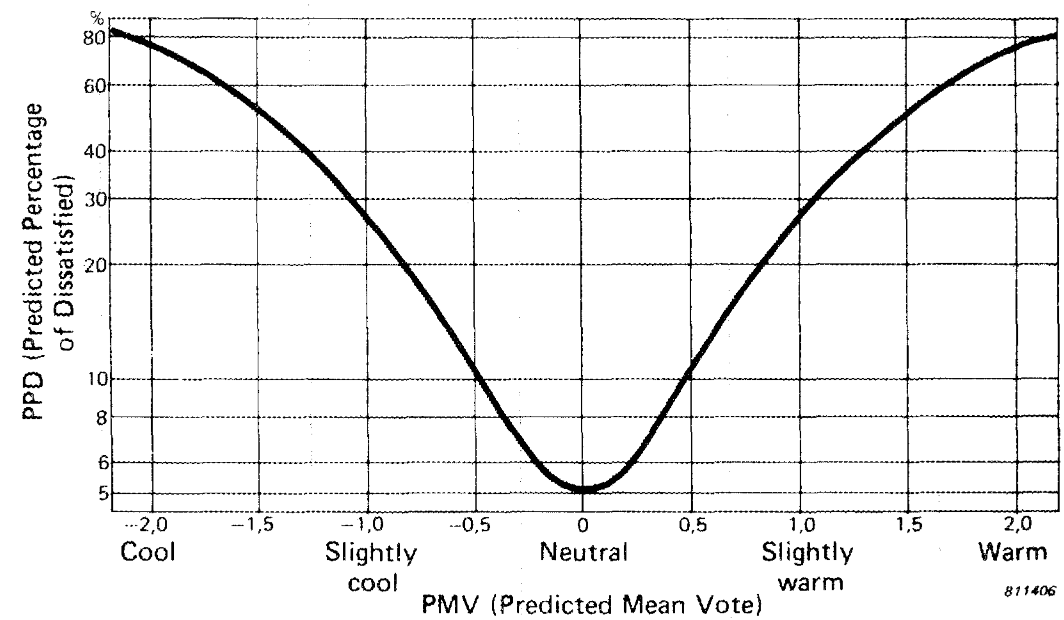

Fig. 3.1. Predicted mean vote (PMV) vs predicted percentage of dissatisfied (PPD). *Source:* Adapted with permission from Brüel and Kjaer, *Thermal Comfort Meter Type 1212,* pamphlet 107-81.

determined by a thermal comfort meter equipped with a transducer capable of sensing human response to the thermal environment. During the 1983 cooling season the thermal comfort meter was periodically placed in different locations throughout the building. The typical office occupant metabolism level was set at 1.2 met [met values represent the probable metabolic rate (or the energy cost) for various typical activities; 1 met = 58.15 W/m^2 = 18.4 Btu/(h·ft^2)] and dressed in a summertime clo value of 0.8 (clo units express the insulating value of clothing; 1 clo = 0.155 m^2·°C/W = 0.879 ft^2·°F/Btu). The relative humidity varied between 40 and 60%. A dew-point meter installed in the return duct provides information on the indoor air moisture content.

Figure 3.2 shows typical PMV measurements taken during the warmest part of the day throughout the summer months at three different locations within the JID. The dashed line in each plot represents typical conditions measured between June 1 and August 31, 1983. The solid lines represent maximum observed PMV in each zone. The scatter of points represents actual measured PMV values. The top plot shows PMV measurements as a function of time in the north-facing office of the building surrounded on three sides by earth-coupled envelope components. The middle plot shows PMV vs time for south-facing dormitory rooms with the south wall consisting of 55% window area and 45% nonvented trombe wall shielded from the solar insolation for the cooling season. The bottom plot shows the PMV vs time for the south-facing offices with 65% of the south wall covered with double-pane windows.

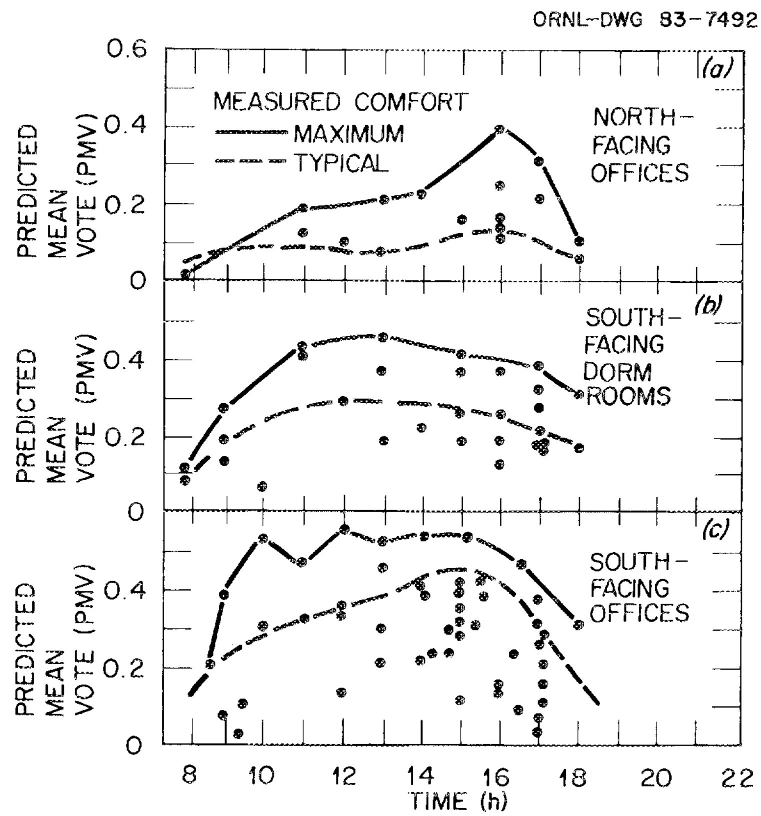

Fig. 3.2. JID thermal comfort measurements in three locations.

The PMV in the summer season varies from 0 (neutral) to 0.5 (90% of the occupants satisfied), which is within the comfort zone specified by ASHRAE 55-1981. The building's south-facing offices remain at a PMV of 0.1, except during the day when the windows transmit heat into the space. The PMV rises from 0.1 to 0.3–0.5, peaking at around 4:00 p.m. The north-facing offices, which are surrounded on three sides by earth, remain closer to a PMV of 0.1 for most of the day and night. However, a very slight upward rise of the PMV from 0.1 to around 0.15–0.2 at 4:00 p.m. is typical.

PMVs for dormitory rooms in the southeast zone of the building with half the south wall glazed, but shielded completely from direct sunlight, show a slight rise from 0.1 to around 0.15–0.3. Throughout the summer, south-facing offices do not have a window management system such as inside blinds or drapes. The daylighting is usually adequate for office work. The footcandle level varies from 350 on the desk nearest the window to 50 on the back desk surface for most of the normal office hours. Blinds on the south windows, installed in November 1983, should help the building during the cooling season by reradiating the solar gain out of the building during unoccupied hours. During occupied hours, the blinds will better disperse the available light in the space and radiate more of the heat coming into the space directly into the thermal mass of the ceiling, thus reducing convective transport (which requires a rise in air temperature before the energy is absorbed by the available thermal mass).

An indication of the comfort conditions in the building can be seen in Fig. 3.3. There are five temperatures plotted hourly on August 4, 1983: the recorded outside air temperature, the south-facing office, the south-facing dormitory rooms, the north zone, and the dew-point temperature recorded in the return duct. The three inside air temperature measurements are taken with shielded thermocouples located 7 cm (3 in.) from the ceiling.

This temperature history shows that the front zones exposed to the south-facing windows will rise about 2.2°C (4°F) to a maximum of 27°C (80°F), whereas the temperatures in the north zones remain day and night at about 24°C (76°F). According to ASHRAE Standard 55-1981, "Thermal Environmental Conditions for Human Occupancy," the maximum acceptable dew point is 17°C (62°F). Figure 3.3 shows that the dew point does rise to about 17°C (62°F) every evening beginning at about midnight and remains close to the maximum allowable condition until noon the next day. This pattern repeats itself until drier weather arrives in July and August, resulting in lower indoor relative humidity.

The building does not overheat in the summertime. Late in August the direct light begins to enter the extensive south-facing glazing and even with 38°C (100°F) outside air temperatures, the building and the 3-ton heat pump keep the space below a 0.5 PMV. Data taken on August 23, 1983, show this (Fig. 3.4). The top plot shows the outside air temperature rising to almost 38°C (100°F). The middle plot shows the heat pump measured sensible cooling. The unit is running continuously from 1200 to 1700. The bottom plot shows that PMV peaks at 0.5 around 1400 and then drops back. The rapid drop between 1500 and 1600 was caused by cloud cover and afternoon showers.

Continuous PMV measurements taken in this building show very little short-term fluctuation of PMV due to compressor cycling. Supply temperature fluctuations are not noticeable, primarily because of the extensive coupling of the inside thermal mass and the supply duct. For comparison purposes, PMV data were recorded in a lightweight office building module equipped with a through-the-wall unitary air conditioner.

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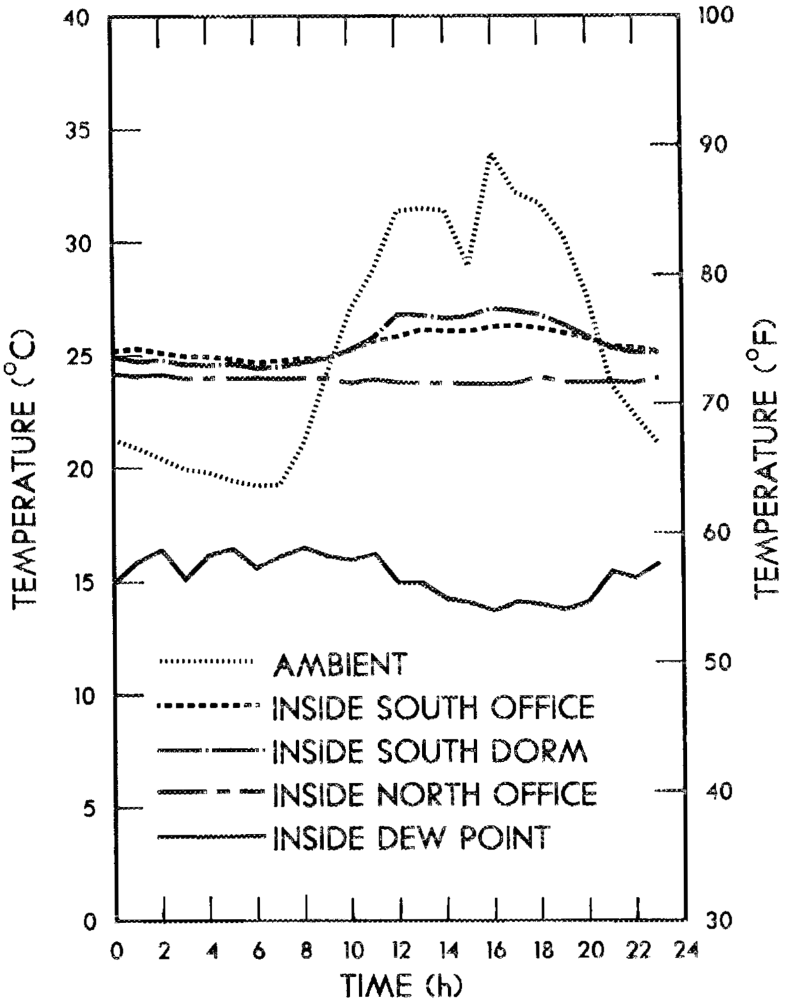

Fig. 3.3. Typical summertime temperature measurements of inside and outside air.

Figure 3.5 shows a plot of PMV in an office located in Oak Ridge, Tennessee, with a 202-kW (7000-Btu/h) unitary air conditioner. With mild cooling requirements, the oversized unit cycles on and off frequently, resulting in thermal stress of the occupant due to the rapid change in comfort conditions. However, turning the circulating fan on continuous operation would reduce the amplitude.

A number of buildings with trombe wall systems have reported overheating problems during the summer. This building has four nonvented trombe walls equipped with an external reflector shield that folds down in the winter and covers the wall in the summer. Figure 3.6 shows the diurnal heat flux cycle measured on both sides of the 12-in.-thick poured concrete wall. The external heat flow sensor peaks at 1600; however, the inside heat flux sensor peaks at 400, a 12-h lag and an attenuation from around 19 W/($m^2 \cdot °C$)

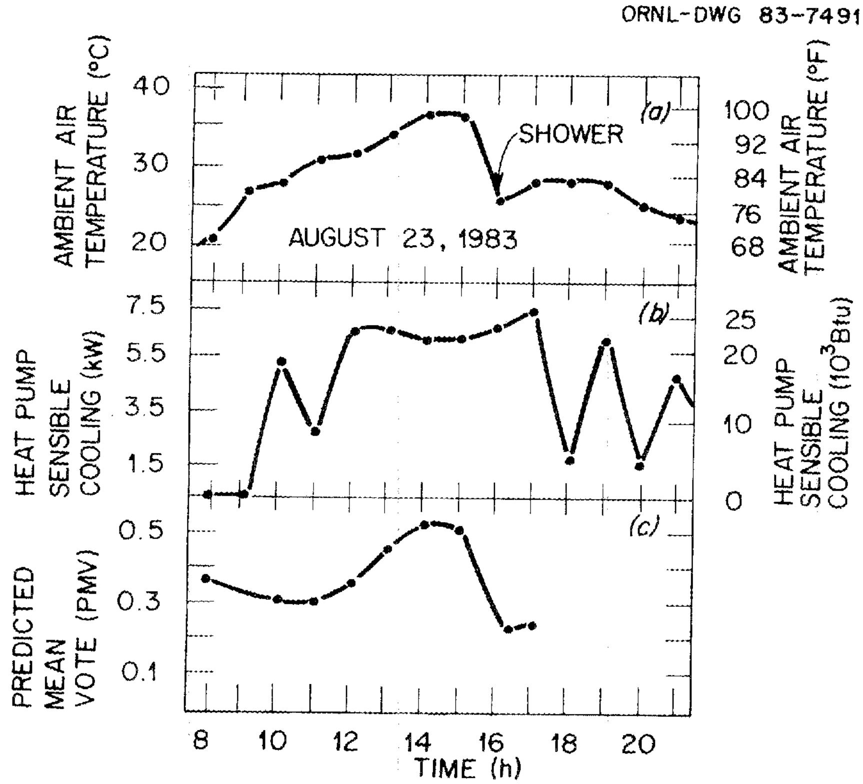

Fig. 3.4. Thermal comfort at 38°C (100°F) peak outside temperature.

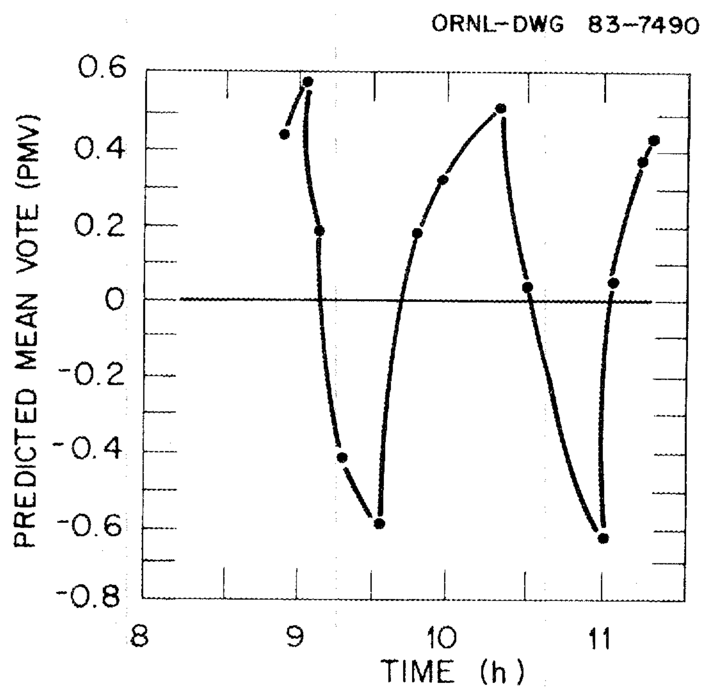

Fig. 3.5. Thermal comfort measurements in a typical office building equipped with a unitary through-the-wall air conditioner.

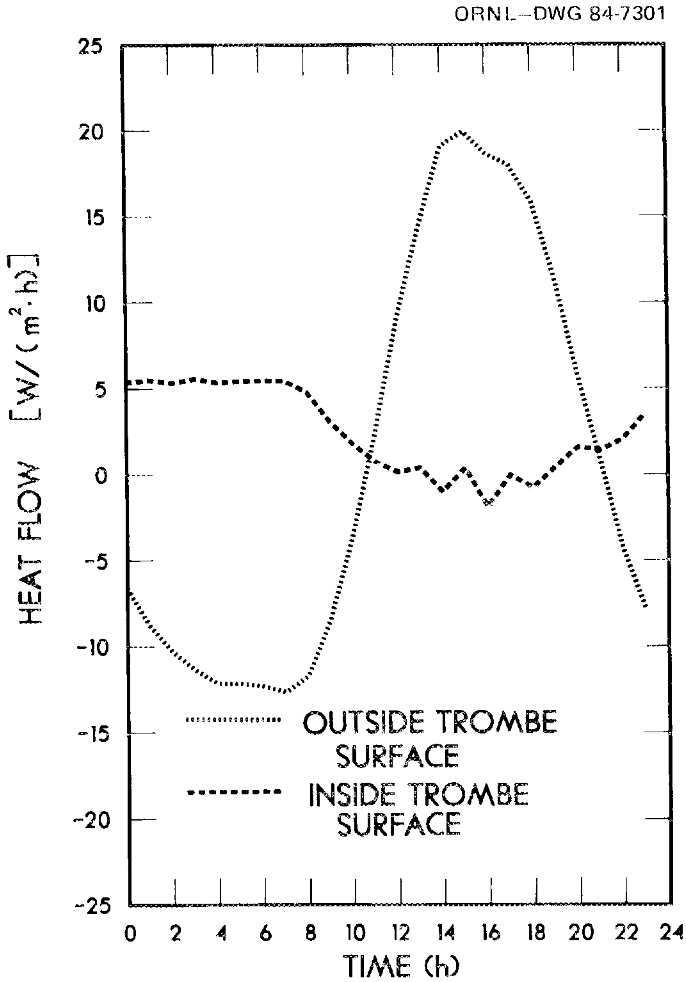

Fig. 3.6. Heat flow through the trombe wall in summer.

[6 Btu/(h·ft^2·°F)] on the outside of the mass to about 6 W/(m^2·°C) [2 Btu/(h·ft^2·°F)] on the inside. The heat flow into the inside air space is out of phase with the dominant cooling load in the building, thus causing very little contribution to the whole-building cooling requirements. The actual amount of heat flowing into the dormitory rooms late at night is comparable to a 25-W light bulb. Therefore, it is not a substantial detriment to thermal comfort.

The thermal comfort measurements reflect a number of points worth emphasizing. First, this passively heated office/dormitory building is thermally satisfactory throughout the cooling season to at least 90% of the occupants even in the warmest location in the building. No thermal comfort penalty is paid in summer months for the 30% energy savings resulting from the building's efficient performance. Secondly, even during record-breaking hot summer days, the very small heat pump, coupled with a massive building, permits satisfactory thermal comfort.

A well-built, energy-efficient building not only saves energy, but can be held to tighter comfort standards even with drastically different inside surface temperatures, such as 22°C

(72°F) at the floor and 32°C (90°F) at the south-facing windows. Occupant performance is related to comfort. A decrease in performance of mental tasks occurs with increasing thermal dissatisfaction. Most offices cannot afford any thermal comfort productivity penalty.

4. WHOLE-BUILDING COOLING SEASON ANALYSIS

4.1 ENERGY USAGE

To heat, cool, and provide continuously circulating air for this 372-m^2 (4000 gross ft^2) office/dormitory in a climate typical of Oak Ridge, Tennessee, costs an average of 60 $/month, assuming current commercial rates of 5.7 ¢/kWh. The direct cost of running the circulating fan continuously is about $15 per month.

Some cooling is required in this building from May through September. In 1982, with a typical cooling season of 655 DD base 18°C (1180 DD base 65°F), the building used 5000 kWh for cooling at a cost of $285, and in 1983 with an above-average cooling season of 724 DD base 18°C (1304 DD base 65°F), the building used 5487 kWh at $313. A 10% increase in cooling DD resulted in an equivalent 10% increase in electric energy consumption. During the cooling season months, 40% of the total electric energy consumed by this building is used for providing mechanical space conditioning.

One full year of electric energy submetered data from May 1982 through April 1983 shows that space conditioning energy for cooling (including continuously running indoor blower) represents 16% of the total electric energy used by the building. The complete energy usage percentage breakdown for 1 year is shown in Fig. 4.1. The monthly measured

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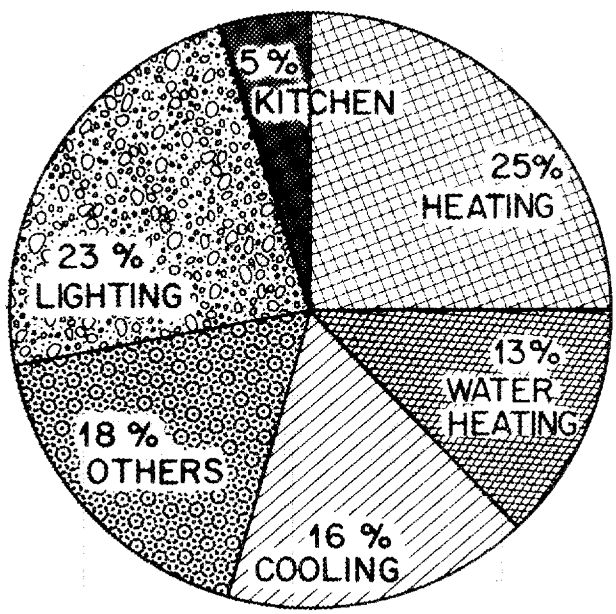
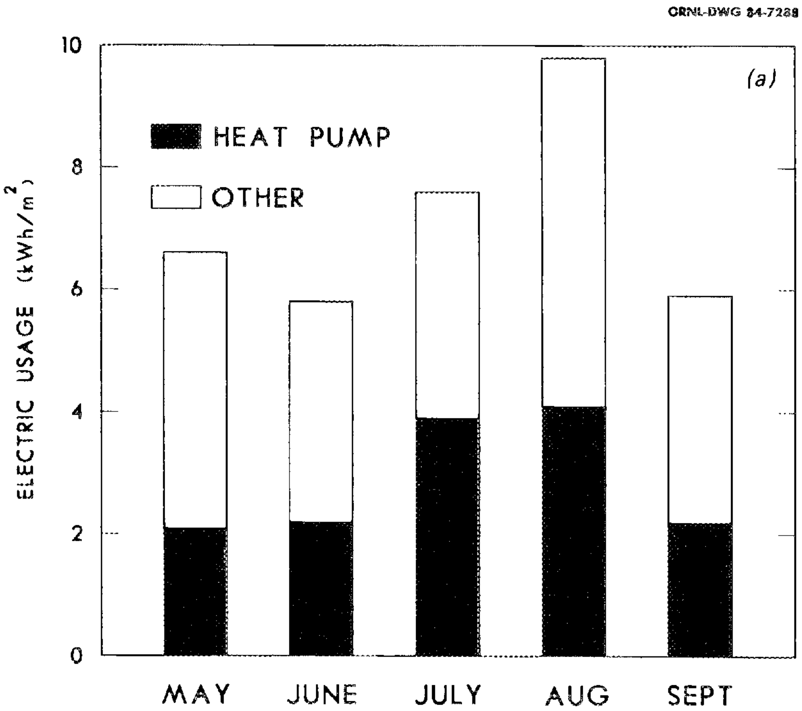


Fig. 4.1. JID whole-building energy usage for June, July, and August of 1982 and 1983.



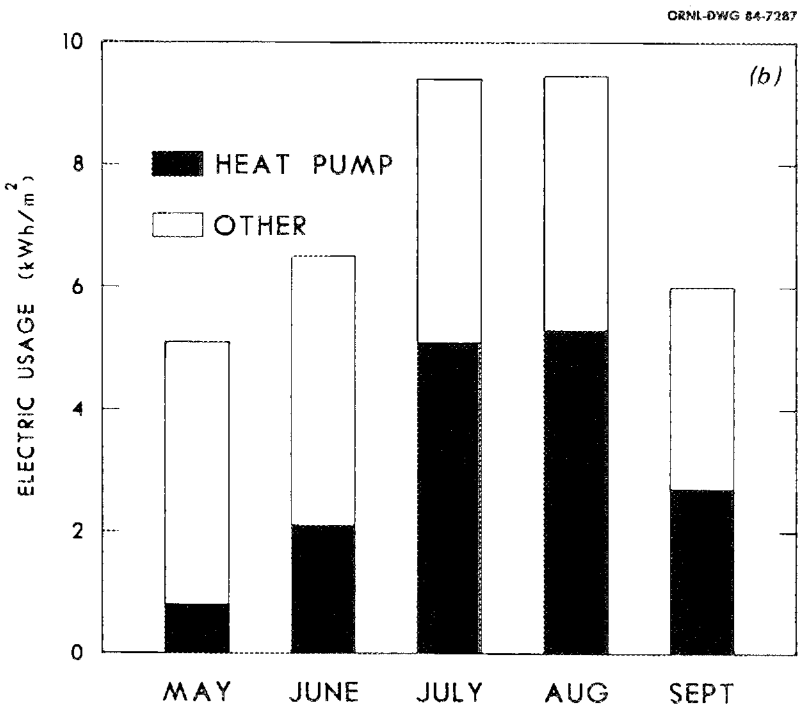


Fig. 4.2. JID monthly energy usage for *(a)* summer 1982 and *(b)* summer 1983.

energy usage values are given in Appendix A, Tables A.1 and A.2. The pie chart is representative of well-built energy-efficient buildings. The total internal energy usage (lights, water heating, kitchen, and other) is similar to that of typical residential buildings. The existing national residential stock of buildings use about 50% of the total incoming energy for heating and about 5–8% for cooling, although more efficient structures being built in the early 1980s show considerably smaller fractions for heating and slightly larger ones for cooling.

The JID occupancy patterns are not much different from those of residential structures. During the day the office space is occupied intermittently because most of the researchers have ongoing experiments in laboratories located in nearby buildings. Throughout the 1982 and 1983 cooling seasons, the total number of people using the building at any one time typically varied from three to seven. A major difference between this building and typical residential buildings is that there are more rooms and closed doors between inside spaces, restricting natural convective heat transfer between zones.

Figure 4.2 displays the monthly energy consumption per square meter of floor area for the whole building and the electric energy used for running the heat pump in 1982 and 1983. Throughout the summer months, the monthly non-space-conditioning energy use averaged about 4.5 kWh/m^2. Detailed submetered data are shown in Appendix A.

4.2 FIELD-MEASURED HEAT PUMP AND ECONOMIZER PERFORMANCE

4.2.1 Heat Pump Steady-State Measurements

The installed single-package unitary heat pump is capable of providing a total cooling capacity of 10.5 kW (3 ton) at 35°C (95°F). The old sizing rule of thumb used for typical office building construction calls for a unit three times this size. Careful direct solar insolation shielding, available daylighting, adequate envelope insulation, and sufficient effective thermal mass coupled with the inside air contribute to a 70% reduction in peak electric demand. Part of this reduction is due to the lower occupancy load since the dormitory rooms are not heavily used during the peak cooling hours. Throughout the summer, this building never overheated to the point where the measured predicted percentage of dissatisfied (PPD) exceeded 10%. With an output of 10.5 kW (3 ton), the unit running continuously for 1 h used 5.2 kWh. If this building were typical of the existing building stock, a 35-kW (10-ton) unit would be required, resulting in peak power input of 15 kW, a factor of three more than that for the JID. This observation leads to a simplified observation that the potential exists to cut the summertime peak power requirement for space conditioning in envelope-dominated buildings by 70% through careful energy-conscious building design.

The heat pump sensible cooling output is determined in part by measuring the return and supply air duct temperatures using averaging resistance thermometers. An anemometer is positioned in a straight section of the return duct, providing a measurement of air flow. These three measurements, along with a calibration constant accounting for duct cross-sectional area, specific heat, and density of the air are used in Eq. 4.1 each hour to determine the sensible cooling supplied.

$$Q = \int_0^\theta q d\Theta = \sum_{okA}^{\theta} \Delta T \ , \tag{4.1}$$

$$q = kA\Delta T \ ,$$

where

θ	=	time,
q	=	sensible cooling per measured period,
Q	=	sensible cooling output from heat pump,
k	=	calibration constant accounting for specific heat, density, and cross-sectional area of the duct,
A	=	anemometer rotations per hour indicating air flow,
ΔT	=	temperature difference between supply and return ducts.

The latent heat removal is determined by measuring the volume of condensate collected from the evaporator coil and converting that to latent heat by use of Eq. 4.2.

$$Q_L = W_{gal} \times 8.34 \text{ lb/gal} \times 1066 \text{ Btu/lb} \ , \tag{4.2}$$

where

W_{gal}	=	gal of condensate collected,
1066	=	latent heat of vaporization at typical conditions (50°F).

Table 4.1 shows a number of hours of measured heat pump sensible and latent heat removal. These hours are representative of the heat pump's performance while running continuously without cycling losses. The nominal cooling capacity and energy efficiency ratio (EER) rated at Air-Conditioning and Refrigeration Institute (ARI) conditions of 35°C (95°F) outdoor air temperature are 11.7 kW (40,000 Btu) and 7.7. The measured heat pump performance suggests that at steady-state operating conditions, the installed heat pump produces only 80% of the rated total cooling capacity, and the resulting EER is about 20% below the ARI-tested performance.

The poor heat pump performance is caused not by the unit itself, but rather by how the unit is coupled with the building envelope.

Figure 4.3 shows a percentage breakdown of the measured sensible and latent heat output for 1 h at 35°C (95°F) ambient air compared with the ARI-rated output at similar conditions. The shortfall in measured cooling performance is estimated based on a variety of factors which cause deviation from the laboratory test conditions. The largest single cause for the low output is that the evaporator fan provides only 67% of the manufacturer's recommended air flow. This low air flow is believed to result from restrictions in the supply duct located in the concrete footings of the building. Either the sheet metal duct deformed during construction of the concrete footings, or the overall coefficient of friction within the supply duct is higher than predicted. The lower air flow past the evaporator coil is

Table 4.1 Hourly steady-state heat pump performance measurements

Ambient temperature		Sensible cooling output		Latent cooling output		Total cooling		Energy efficiency ratio (EER)
°C	°F	kW	Btu/h	kW	Btu/h	kW	Btu/h	
31	87	6.1	20,714	4.1	14,000	10.2	34,714	6.7
32	89	5.6	19,014	2.3	8,000	7.9	27,014	5.2
29	85	6.7	22,975	3.2	11,000	10.0	33,975	6.5
34	93	6.2	21,169	3.3	11,300	9.5	32,469	6.2
35	95	6.2	21,280	2.0	7,000	8.2	28,280	5.4
35	95	6.4	21,901	2.6	9,000	9.0	30,901	5.9
36	96	6.3	21,612	2.9	10,000	9.3	31,612	6.1
33	92	6.2	21,279	3.8	13,000	10.1	34,279	6.6
Average						9.3	31,646	6.1
Nominal						11.7	40,000	7.7

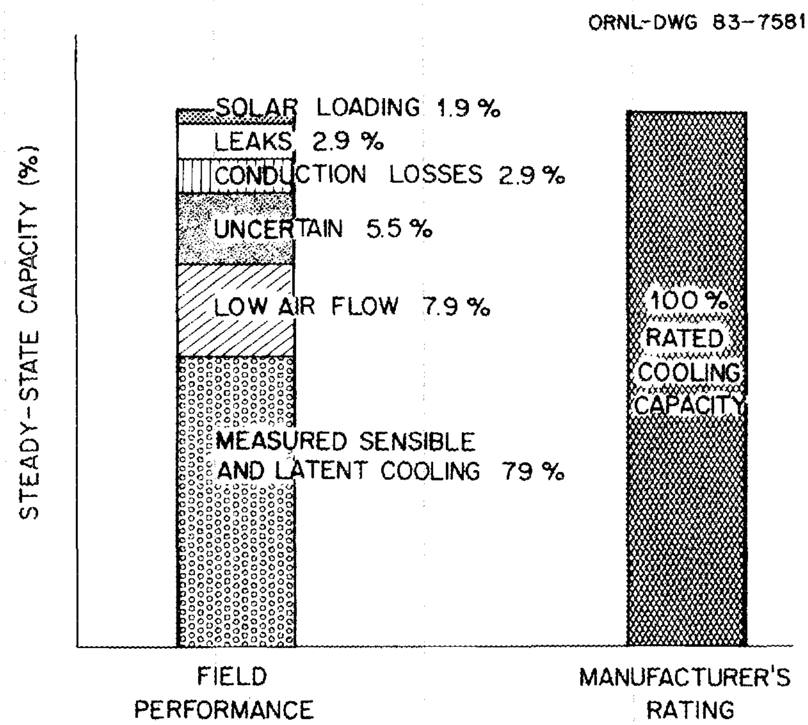


Fig. 4.3. JID heat pump steady-state performance at 35°C (95°F) outside air temperature.

estimated to reduce the cooling output at rated conditions approximately 8% from the manufacturer's data. Another 8% loss results from a combination of air leaks from the return duct and economizer, conduction losses due to wet insulation on the floor of the heat pump housing and missing insulation on the return duct, and the radiative loading of the sun. The surface temperature of the heat pump housing in the afternoon with full sun has been measured as high as 68°C (153°F).

The cause for the remaining difference between measured and ARI-tested performance is unknown, although part of the remaining shortfall in cooling performance could be due to the location of the heat pump on the west side of the building and the fact that it is surrounded by the building and retaining wall. With the afternoon sun, this location heats up above ambient conditions, causing the heat pump to use a slightly hi-her condenser inlet air temperature than measured by the electronic thermometer collecting site ambient air temperatures in front of and above the heat pump housing.

4.2.2 Heat Pump Seasonal Performance

The average seasonal energy efficiency ratio (SEER) for delivering only sensible cooling is around 4.5. The value is low, not only because of the installation shortcomings mentioned above, but also because of the continuous circulating fan. Figure 4.4 shows the EER of a variety of heat pumps with continuous and automatic fan operation.[5] The continuous fan penalty becomes very apparent at part load capacity.

Occasionally, when cooling is not needed in the building but the outside air temperature is rising, the sun shining down on the heat pump housing located on the west side of the building results in a heat load of as high as 1700 W/h (6000 Btu/h). Part of this heat gain is due to the fan power (400 W). However, the fact that this represents about 25% of the maximum sensible cooling capacity illustrates the significance of this solar loading.

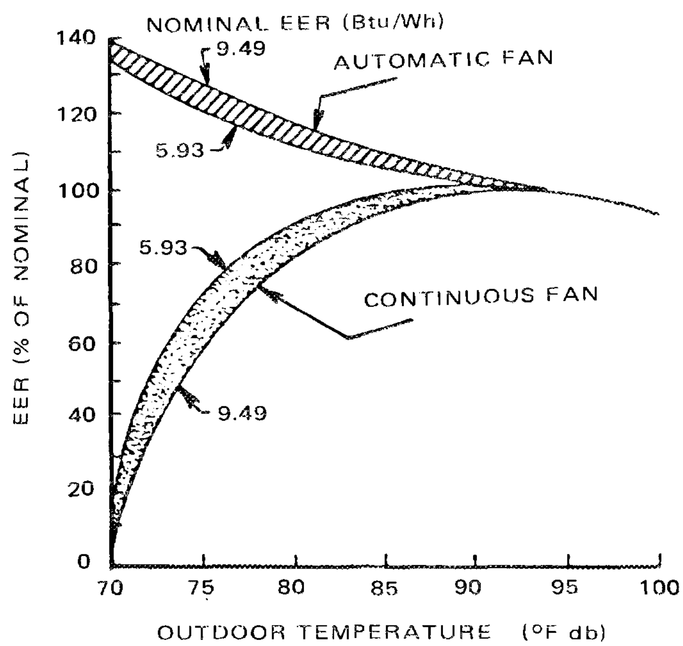


Fig. 4.4. Percent of the nameplate EER (Btu/Wh) vs outdoor temperature for continuous and automatic fan operation. *Source:* J. E. Christian, *Unitary and Room Air Conditioners*, ANL-CES/TE 77-5, Argonne National Laboratory, September 1977.

A more efficient mechanical design for the building would be to use a split heat pump system for providing heating and cooling. The inside unit could circulate air without picking up heat, and the economizer could be reconfigured so the inside fan unit could also pull in outside air for ambient cooling when conditions were acceptable. A second opportunity for improving the coupling between the building envelope and the mechanical package would be to incorporate a heat exchanger for bringing in ventilation air and recovering some of the lost cooling in the summer and heat in the winter.

During the summer months, a dominant heat load to the building is from internal electric usage. The daily value fluctuates according to the building occupancy, although on a monthly basis it is fairly constant. The building envelope is well shaded from the direct sunlight and shielded from the wind so the remainder of the heat gain is proportional to the inside and outside temperature difference.

The monthly heat pump energy use from May through September for both 1982 and 1983 is plotted against monthly cooling DD in Fig. 4.5. The straight line is the least squares regression fit for the monthly data. The cooling DD base 20°C (68°F) was found to provide the Y intercept closest to 300 kWh, which is the constant monthly consumption for the circulating fan. This suggests that the average balance point for the building is also 20°C (68°F). When the outside air temperature rises above this temperature, cooling is generally required. The slope of the regression line is 4.3, which indicates that 4.3 kWh is required for every cooling DD base 20°C (68°F).

The correlation coefficient for the regression equation shown in Fig. 4.5 is 0.96. In general, the equation is capable of predicting monthly heat pump energy requirements for the building within ±20%.

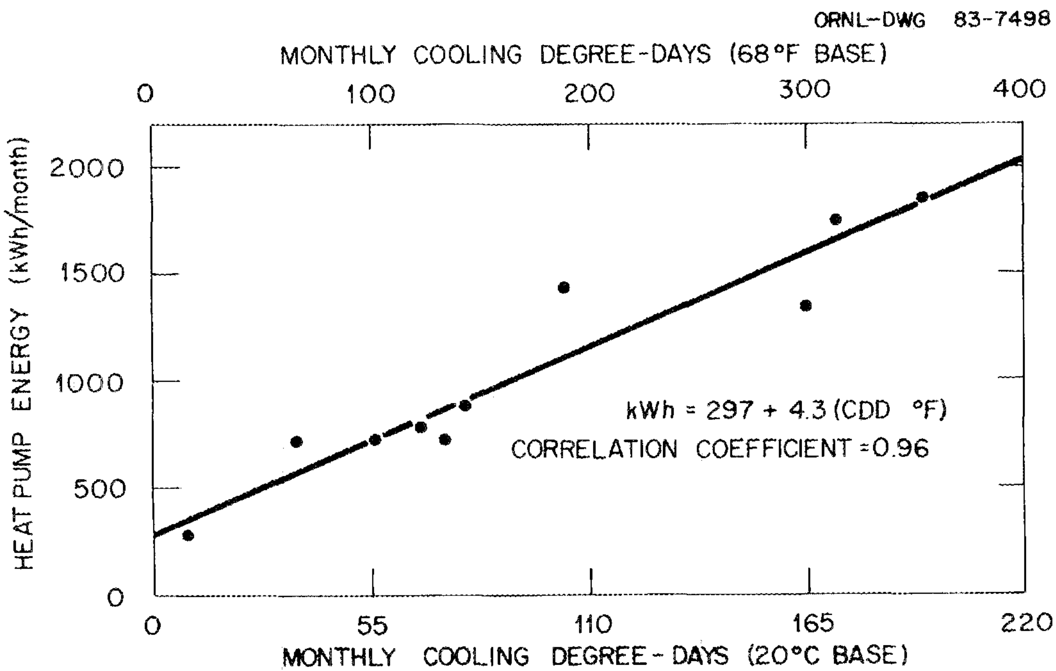


Fig. 4.5. Monthly heat pump energy usage vs cooling DD—May–September 1982 and 1983.

The least squares fit of heat pump energy consumption and cooling DD represents a data fit to a steady-state heat transfer model that suggests that the cooling load is simply a function of the average temperature difference between the inside and outside air. The direct influence of the sun on this building is almost negligible because of the earth covering and the extended overhang on the south side.

A second parameter that will cause a discontinuity in the linear relationship of energy consumption and cooling DD is the latent load. Figure 4.6 shows that the latent load is proportional to cooling DD, largely because the thermostat is controlled only by the sensed dry-bulb temperature in the building, and the more the unit runs, the greater the latent heat removal.

4.2.3 Economizer Performance

The economizer is coupled in series with the heat pump and is positioned on the return duct side of the heat pump. An enthalpy controller senses the air temperature surrounding

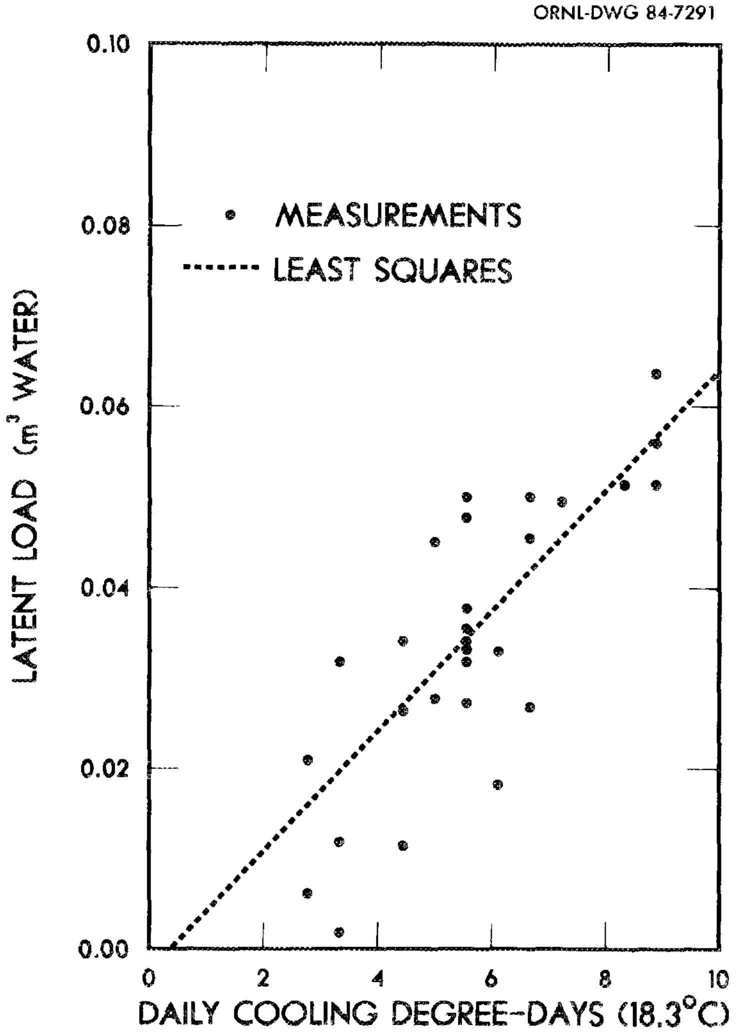


Fig. 4.6. Cooling DD vs latent cooling of JID heat pump.

the unit and the moisture in the air. If the enthalpy is below the set points, outside air is pulled in to cool down the building air and mass with ambient cooling. Earth-sheltered homes are usually designed to minimize exposure to the wind, resulting in lost opportunity for natural cross ventilation, but an economizer helps enhance ambient cooling by increasing the ventilation rate (in this case by a factor of 10).

Table 4.2 shows the amount of sensible cooling provided by the economizer for a variety of weeks throughout 1982 and 1983. It is apparent that a larger fraction of economizer cooling takes place in early and late summer, ranging from 40 to 70% as compared with 0% when the temperature remains relatively high during midsummer nights.

Table 4.2 Economizer cooling

Week	Measured heat pump sensible cooling (kW)	Measured economizer sensible cooling (kW)	Percent economizer total
	1982		
June 21–27	143	115	45
June 28–July 4	150	76	34
August 9–15	560	0	0
August 16–22	337	33	9
August 23–29	280	0	0
	1983		
June 13–19	81	230	74
June 20–26	306	156	34
June 27–July 3	312	17	5
July 4–10	249	0	0
July 11–17	513	151	23
July 18–24	523	0	0
July 25–31	492	0	0
August 1–7	477	10	2
August 8–14	427	70	14

The physical location of the economizer hinders the maximum use of ambient cooling for many of the same reasons the heat pump performance is impaired. The heat pump and economizer are surrounded by mass. This absorbs heat from the sun and from the heat pump condenser coil all day and into the night. Then, when the ambient air finally cools down enough to provide some cooling assistance, the economizer senses the surrounding warm radiating mass and keeps its dampers closed.

However, the high humidity in the area generally restricts the economizer cycle operation throughout most of the summer. During the 1983 summer months of June, July, and August, the economizer sensitivity was set at position *A* shown by the psychrometric chart in Fig. 4.7. In the early morning hours from 100 to 600, when the ambient temperature is lowest, the average relative humidity is usually above 90%. But the air temperature must be below 17°C (63°F) to permit the economizer cycle operation. In only 9 d of July and August 1983 was the dry-bulb minimum temperature below 17°C (63°F) for at least 1 h.

CONTROL CURVE	CONTROL POINT (APPROX. DEG.) AT 50% RH
A	23.0 (73)
B	20.0 (68)
C	17.0 (63)
D	14.5 (58)

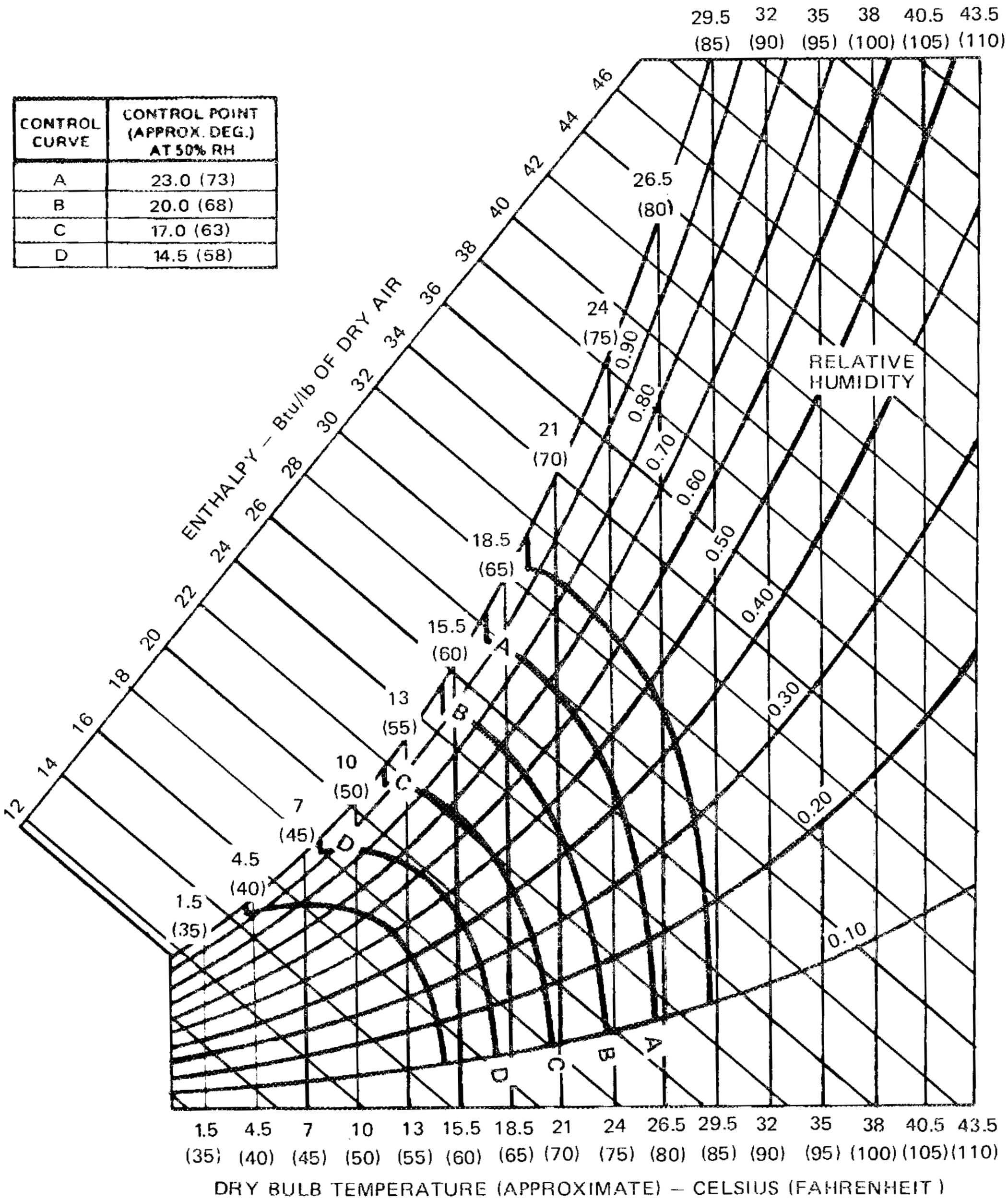


Fig. 4.7. Psychrometric chart showing economizer enthalpy controller set point *A*. *Source:* Adapted with permission from Honeywell, Inc., *Honeywell Enthalpy Controller for Economizer H205A.*

Nighttime ventilation coupled with extensive structural thermal mass can provide significant annual and peak energy savings in commercial buildings. However, in those parts of the country with high humidity, this option is severely restricted.

A close examination of the heat pump efficiency and economizer performance suggests that when whole-building comparisons are made, differences in the mechanical plant must be considered. Very efficient heat pumps installed in residences near the JID have SEERs exceeding 8, and the heat pump at JID has an SEER of around 6. A very efficient building envelope and mechanical package do not guarantee an optimum whole-building design. Careful coupling of the two systems is necessary to reach the whole-building energy efficiency potential.

4.3 ENERGY SAVINGS COMPARED WITH ABOVEGROUND BUILDINGS

4.3.1 Efficient Residential Buildings

There are a number of energy-efficient building envelope concepts included in the JID. The combination of all the features results in an energy-efficient building. It is unlikely that this building will be replicated in numerous other sites and have similar usage patterns, but many of the features will be used in other buildings. Field performance data for the individual conserving concepts would probably be most useful. However, to save energy in a building year round, the energy savings credited to one feature is a function of its interaction with many other features within the building design.

A comparison of the JID whole-building performance to that of a well-built, above-grade frame structure is probably most meaningful. The comparison highlights the effect of massive vs light frame construction; earth covering vs energy-efficient, aboveground frame envelope; and extensive south-facing window area vs more distributed windows.

The above-grade, energy-efficient residential building used for comparison is the TECH House III, located approximately 25 miles from the JID site. It was very carefully monitored throughout the 1982 summer season. This house, described in Sect. 1, is part of the TECH complex building research facility operated jointly by the University of Tennessee and ORNL.[3] The programmed interior electric and occupancy usage of the TECH House III is approximately the same as that of the JID, when normalized to a unit floor area per month value (4.5 kWh/m^2).

The total monthly energy usage in kilowatt-hours per square meter for the TECH House III is shown in Fig. 4.8 along with that for the heat pump alone. Comparing only the heat pump energy consumption of the TECH House III with that of the JID reflects a 30% savings for the JID. If the JID heat pump were performing at the higher SEER measured in the TECH House III, the electric energy savings would be greater than 50%. Additionally, if the continuous circulating fan were unnecessary, the electric energy savings would exceed 60%.

In addition to the annual energy savings, the peak cooling requirements are cut almost in half. The TECH House III has an installed cooling capacity equivalent to 57 W/m^2 (18 Btu/ft^2) compared to the JID's 31 W/m^2 (10 Btu/ft^2).

The increased cost for going below ground is estimated at about 12 $\$/ft^2$ using Knoxville area labor.[6] For comparison, the same floor plan placed in an aboveground structure would result in the underground JID structure saving 60% in cooling and heating energy. This results in an annual electric energy savings of about 500 \$/year based on 5.7 ¢/kWh, or a simple payback of 95 years, not accounting for the other environmental amenities inherent in underground construction.

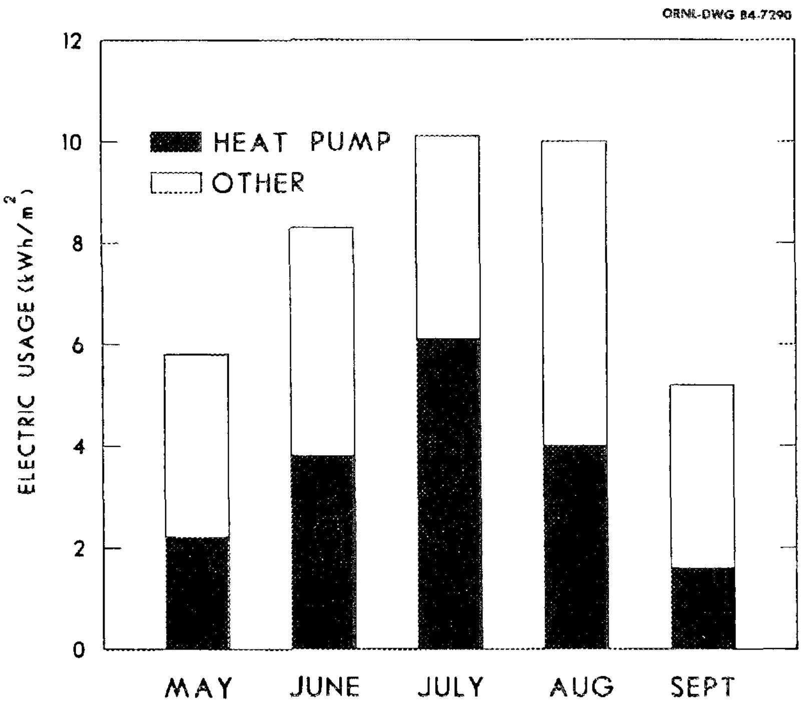


Fig. 4.8. Energy consumption for energy-efficient, above-grade residential building (TECH House, summer 1982).

4.3.2 Conventional Commercial Structures

A nearby ORNL office building, built in the late 1970s, is used for a comparison with the JID. This two-story office building has a total floor area of 600 m^2 (6500 ft^2). An individual 2-kW (7000-Btu/h) air conditioner is located in each of the 29 offices. The total building cooling capacity [60 kW (203,000 Btu/h)] is equivalent to the budget estimating rule of thumb (280 ft^2/ton), three times the installed capacity in the JID. The roof has an RSI of 3.5 (R = 20) and the walls have an RSI of 2.3 (R = 13), which is typical for currently constructed commercial office space. After correcting for floor area the slightly higher internal electric loads in the office building by adding an increment of cooling necessary to remove this internal heat source, the JID was found to use 5% less energy for cooling than this office building in June, July, and August of 1982. For the same three months in 1983, the JID used 30% less electric energy for space conditioning. This savings would be considerably larger if the office building were conditioned around the clock. The units are typically turned on by the office occupants in the morning and turned off by janitorial personnel in the early evening. Thus, the office building is conditioned for less than a half day for 5 d/week, or about a third of the amount of time the JID is maintained within the comfort zone.

If the office building were conditioned continuously, the load would triple, and it would use three times the energy of the JID. Thus, if the JID uses $300 a cooling season, then a savings of around 600 $/year is obtained. If the same kind of savings could be obtained for the winter season, $800 could be saved for a total of 1400 $/year.

4.3.3 DOE-2.1A Building Simulation Model

The DOE-2.1A building simulation model, described in Sect. 1, was used to model both the JID and an aboveground structure. The annual savings for the entire year, both cooling and heating, was about 30%. The first-cost construction difference between commercial structures built above ground and earth-sheltered buildings appears to be minimal for small commercial structures. This impression was drawn from cost comparisons between the JID and other small buildings built at the Oak Ridge National Laboratory.

4.3.4 Summary

Compared with residential aboveground buildings, the earth-sheltered building clearly saves energy. However, at today's cost for electricity, the payback for going below grade does not appear to be very favorable without accounting for the environmental amenities, such as sound barrier, visual screen, and less land requirement per lot for smaller residential buildings. If the cost of energy were to triple from 5.7 ¢/kWh to 17 ¢/kWh, this would bring the whole-building payback from the 95-year simple payback range down to the 30-year range.

5. BUILDING ENVELOPE PERFORMANCE

In the last section, the amount of energy needed to maintain the JID during the cooling season was discussed. The data acquisition system installed in the building permits an insight into those sources of heat entering the building which require mechanical removal. For instance, the fraction of sensible cooling caused by the envelope can be determined; and, more specifically, the amount of heat entering the building from the earth-covered roof and bermed walls can be determined. Weekly sensible energy balances determine the major heat gains and losses in the building and provide a representation of the envelope performance during a cooling season.

Five weekly energy balances were calculated on the building using measured data from the 1982 cooling season. The detailed weekly energy balance calculations are provided in Appendixes B–G. After each energy balance calculation, a summary table (Tables B.1–G.1) for each week shows the sum of measured energy gains compared with measured energy losses. Table 5.1 shows the average percentage breakdown of total sensible heat flow in the building. Figure 5.1 shows the largest source of heat in the building is the internal loads (electric usage and occupants). Throughout the summer months, the internal electric heat source represents about 50% of the total sensible heat gain to the building. The second largest heat source is the south-facing windows. The glazing aperture is fully shaded from

Table 5.1 Weekly energy balances (%)

Source	Week 26		Week 27		Week 33		Week 34		Week 35		Average	
	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses	Gains	Losses
Internal loads	49.0		40.0		44.2		62.3		43.4		48.0	
Windows	43.0		47.0		49.0		33.2		40.6		42.0	
Outside walls	3.5		3.4		2.8		2.2		2.4		2.9	
Roof	4.2		5.0		2.3		0.9			2.6	2.0	
Trombe		0.2	0.15		0.3		1.4		0.6		0.5	
Ventilation		9.0	5.2		0.0			3.4		5.3		2.5
Bermed walls		10.4		7.8	1.4			4.9		4.8		5.3
Floor		16.0		18.6		0.0		9.4		11.6		11.1
Economizer		23.0		15.2		0.0		5.2		0.0		8.6
Heat pump		27.0		30.0		109.0		53.5		44.5		52.8
Unknown		13.5		28.6		(−9.0)		23.7		23.8		16.1

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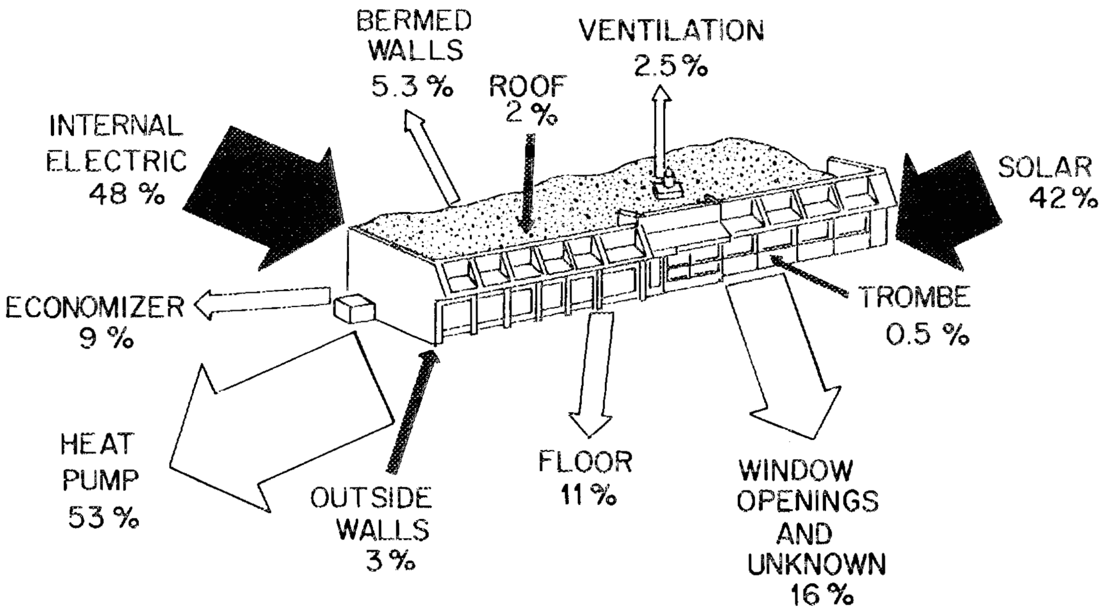

Fig. 5.1. Average energy flows around JID for summer of 1982.

direct solar insolation by the extended overhang, yet the sky radiation and ground reflectance still contribute about 40% of the total heat gain. Less than 10% of the sensible heat gain enters the building through the outside walls and earth-covered roof over a typical diurnal cycle.

The heat losses or sensible cooling comes predominantly from the heat pump (53%). The economizer removes an average of about 9%. This figure is somewhat misleading in the sense that in the beginning and end of the cooling season, when evenings are cooler, the economizer provides a much more substantial cooling contribution. The 5 weeks used for characterizing the cooling season energy balance are all from June, July, and August. A significant fraction of the heat is absorbed by the bermed walls and floor (15%). This contribution is much greater in the first half of the cooling season than the last half since the surrounding earth temperature in the berm lags roughly a month behind ambient air temperature, and the earth below the floor lags about 3 months.

The unmeasured and unaccounted residual energy varied from −9 to 28% on a weekly heat balance period. All but 1 of the 5 weeks had unaccounted heat losses, which most likely resulted from occupants opening windows predominantly in the evening. The detailed energy balance calculations are shown in the appendixes.

Energy balances for time periods of 1 d or longer mask what really happens throughout the diurnal cycle. The peak cooling load occurs in the afternoon because of the extensive use of the building during this period, maximum solar loading, and large inside-to-outside air temperature differences. Figure 5.2 shows an energy balance for a 1-h period at 4:00 p.m. with full sun and outside air temperature of 32°C (90°F). The heat gain exceeded the heat

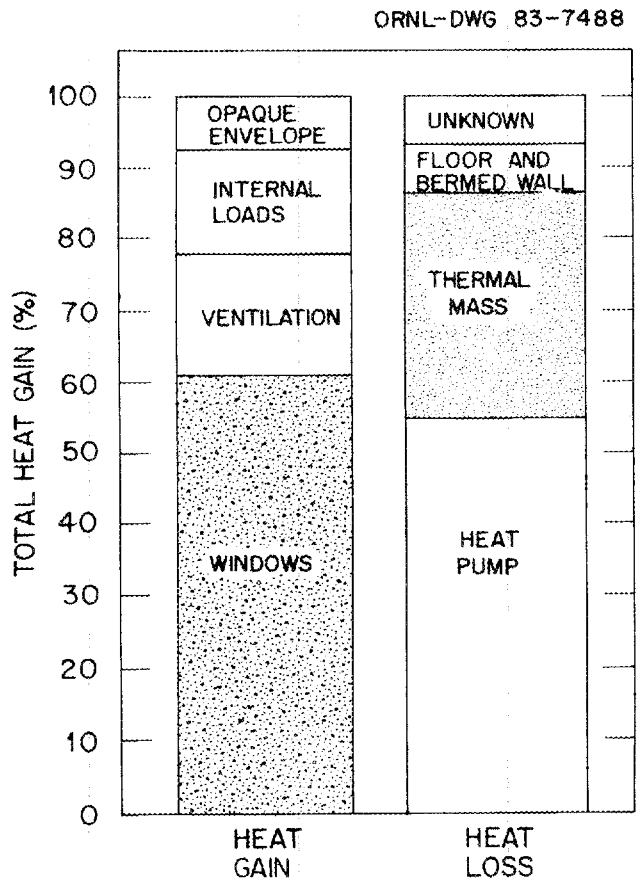

Fig. 5.2. Peak hourly energy balance showing 30% of the incoming sensible heat stored in thermal mass.

pump sensible cooling capacity by 50%, and the inside air temperature remained stable. The thermal comfort within the space was maintained. This excess heat was absorbed by the mass inside the building.

By far the dominant source of incoming heat was the south-facing windows (60%). The internal electric loads for this 1 h are only 15% (0.4 W/ft^2 or 1.3 W/m^2) of the total heat gain, and ventilation accounts for about 16%. The opaque envelope components contribute only 9%, largely because the earth mass surrounding the building absorbs the solar insolation.

Interior mass surface temperatures record between a 0.06°C (0.1°F) and 0.2°C (0.3°F) increase. Table 5.2 shows the heat stored within the interior mass of the various building components for the 1-h balance period. Within the insulating envelope there is thermal mass, primarily in the concrete block partition walls, floor slab, ceiling, poured concrete bermed walls, and concrete block walls insulated on the outside by foam board insulation. Table 5.2 contains the variables used in the simplified expression for thermal mass storage shown by Eq. 5.1. This estimating technique estimates that 3.13 kW (11,000 Btu) of energy, which is equivalent to 31% of the incoming heat for this 1-h period, is stored in the interior thermal mass.

Table 5.2 Energy stored in thermal mass over a 1-h period

Building component	Surface area		Specific heat		Density		Effective thickness		Temperature rise		Energy storage (Btu)
	m^2	ft^2	J/(kg·K)	Btu/(lb_m·°F)	kg/m^3	lb_m/ft^3	m	ft	°C	°F	
Partition walls	158	1704	920	0.22	1920	120	0.1	0.33	0.11	0.2	2970
Floor	345	3714	800	0.19	2323	145	0.1	0.33	0.05	0.1	3377
Ceiling	345	3714	800	0.19	1920	120	0.1	0.33	0.05	0.1	2795
Bermed walls	114	1227	800	0.19	2323	145	0.1	0.33	0.05	0.1	1116
Side walls	46	495	920	0.22	1920	120	0.1	0.33	0.05	0.1	431

During this hour energy was stored in all the thermal mass in the building except that surrounding the supply duct. During the day when cooling is needed, the supply duct temperature is generally below the surface temperature of the mass surrounding the duct. Thus, the mass releases some of its heat, resulting in a reduction in the delivered sensible cooling by about 15%. At night, this mass surrounding the supply duct stores heat from the building, releasing the available sensible cooling.

To use Eq. 5.1 for estimating thermal mass energy storage, it is necessary to assume some value for the effective thermal mass thickness. The use of 0.1 m (0.33 ft) for estimating the energy storage in the interior thermal mass is consistent with ref. 7.

$$Q_{\text{stored}} = \Delta T_{\text{surface}} \times \text{specific heat} \times \text{density} \times \text{exposed surface area} \times \text{effective thickness} \ , \qquad (5.1)$$

where

ΔT = average temperature increase .

A second estimating technique for calculating thermal mass storage uses Fig. 5.3 from the thermal mass assessment[7] to show the energy storage per unit area of each surface. This curve was developed by the use of an exact analytical solution to heat transfer in an envelope component with sinusoidally varying surface temperatures. The measured surface fluctuations within the JID are close to 0.6°C (1°F) for the diurnal cycle. Thus, Fig. 5.3, along with the properties shown in Table 5.2, can be used to calculate the daily storage for a given building component. Assuming that at least 12 h is used to store this much energy, then one-twelfth of the energy should be at least as great as the energy stored during the peak cooling load hour. Using the energy storage values shown in Fig. 5.3, along with interior mass surface areas within the JID, an energy storage value can be calculated at 3.9 kWh, which is very close to the 3.1 kWh produced from the simplified technique shown by Eq. 5.1.

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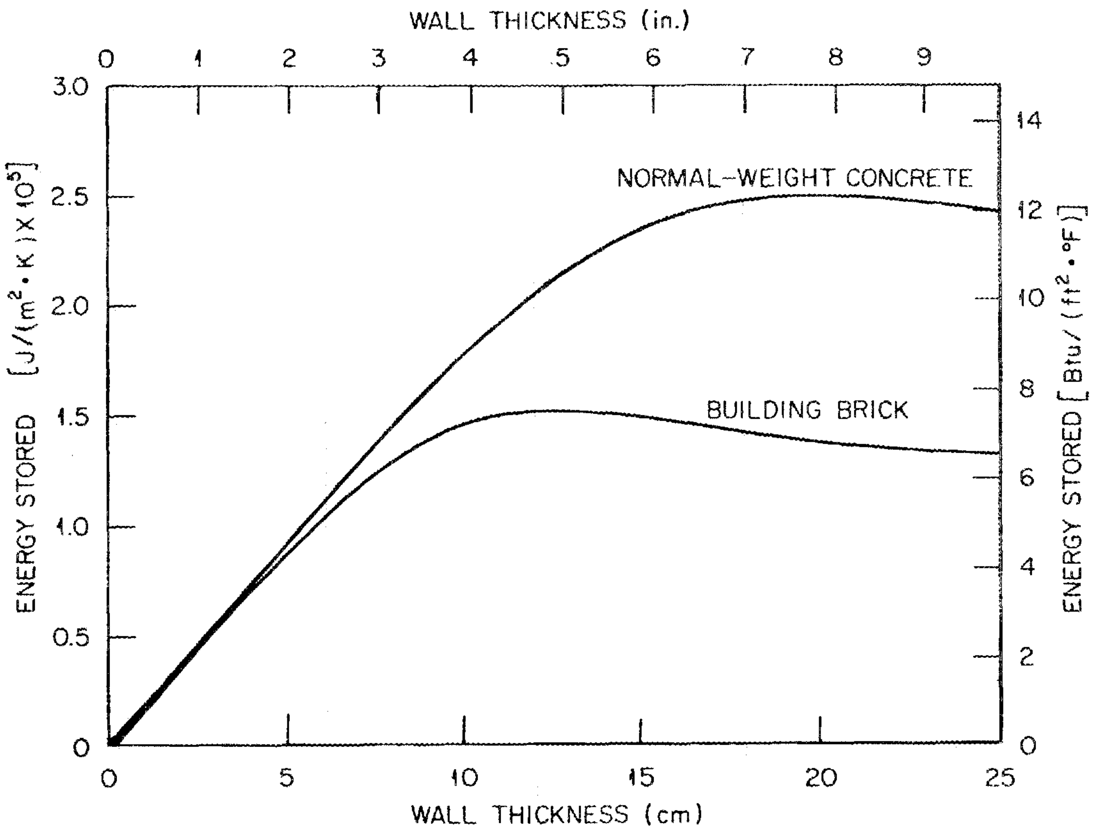

Fig. 5.3. Diurnal energy stored in walls with a 1° surface temperature change.

0.1 m (0.33 ft) from each exposed inside surface, the amount of thermal energy storage is estimated. Because of this storage effect, the building uses only one-half of the peak cooling capacity necessary to maintain thermal comfort in a light frame house, such as the TECH House III. The remainder of this section examines more closely the behavior of the specific envelope components.

5.1 SLAB FLOOR

The floor is an insulated slab with 0.02 m (1 in.) of rigid insulation board placed underneath the poured concrete. Five heat flux sensors are positioned in the floor, two buried just below the tiling and three immersed in a precast concrete block positioned in the gravel just below the slab insulation. Throughout the 1982 summer the average earth temperature 1 m below the floor surface was 19°C (67°F), and in 1983 it was 22°C (71°F). The average heat flow out of the building and through the floor fluctuates very little; this average is about 1 W/m^2 [0.3 Btu/(h·ft^2)]. The sensors on both surfaces of an insulated slab floor agree within 30% of each other over a 1-week period, although the hourly data illustrate considerable erraticism in the sensor placed underneath the tile. Figure 5.4 shows the average hourly measured heat flux through the floor for each week from June 1 to

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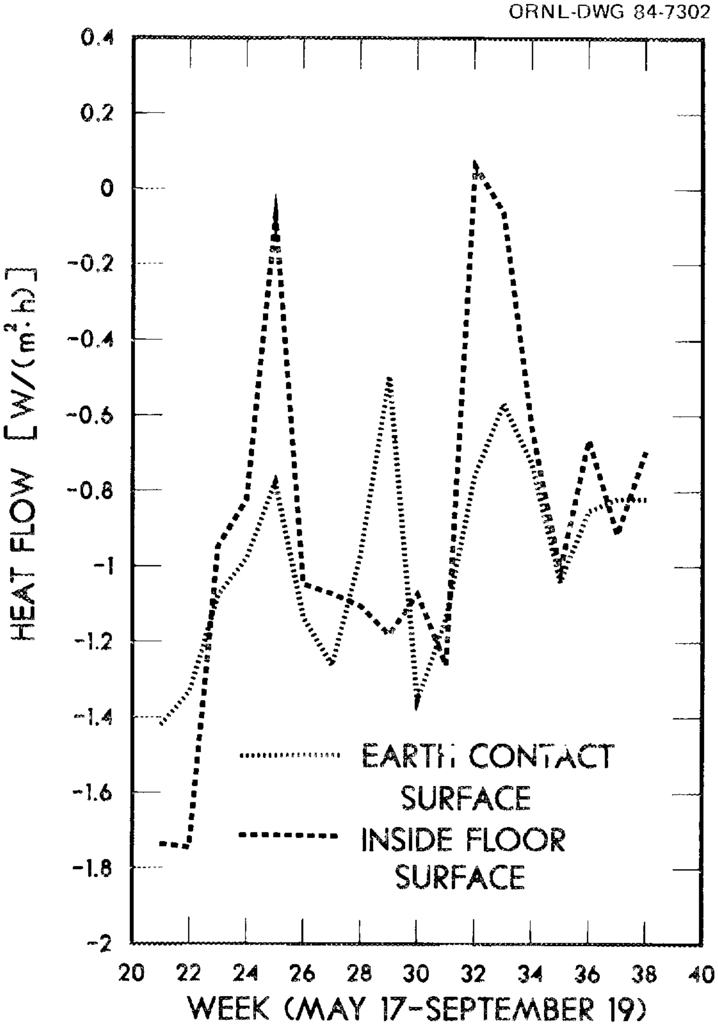

Fig. 5.4. Average hourly heat flow rate through the floor measured for each week from June 1, 1982, through August 1982.

August 31, 1982, from two heat flow sensors positioned toward the middle of the floor slab. The average temperature differences across the floor slab and the estimated RSI of 1.6 (R = 9 h·ft^2/°F) indicate that the sensor positioned below the floor is more representative of the true heat flow leaving the floor slab. The 30% higher measured heat into the slab suggests either measurement error or the existence of multidimensional heat flow.

The heat flow through the slab floor with well-insulated footings appears to be accurately modeled by assuming steady-state heat transfer using average weekly temperatures. However, some uncertainty exists in the estimation of the temperatures to use for the soil below a similar building without thermocouple wells installed below the floor. In this building, a temperature profile taken on the south side of the building would overestimate the soil temperature all summer, and a soil temperature profile on the north side would underestimate the soil temperature until the middle of August. Figure 5.5 shows such temperature profiles for the JID as a function of depth, time, and location. The floor

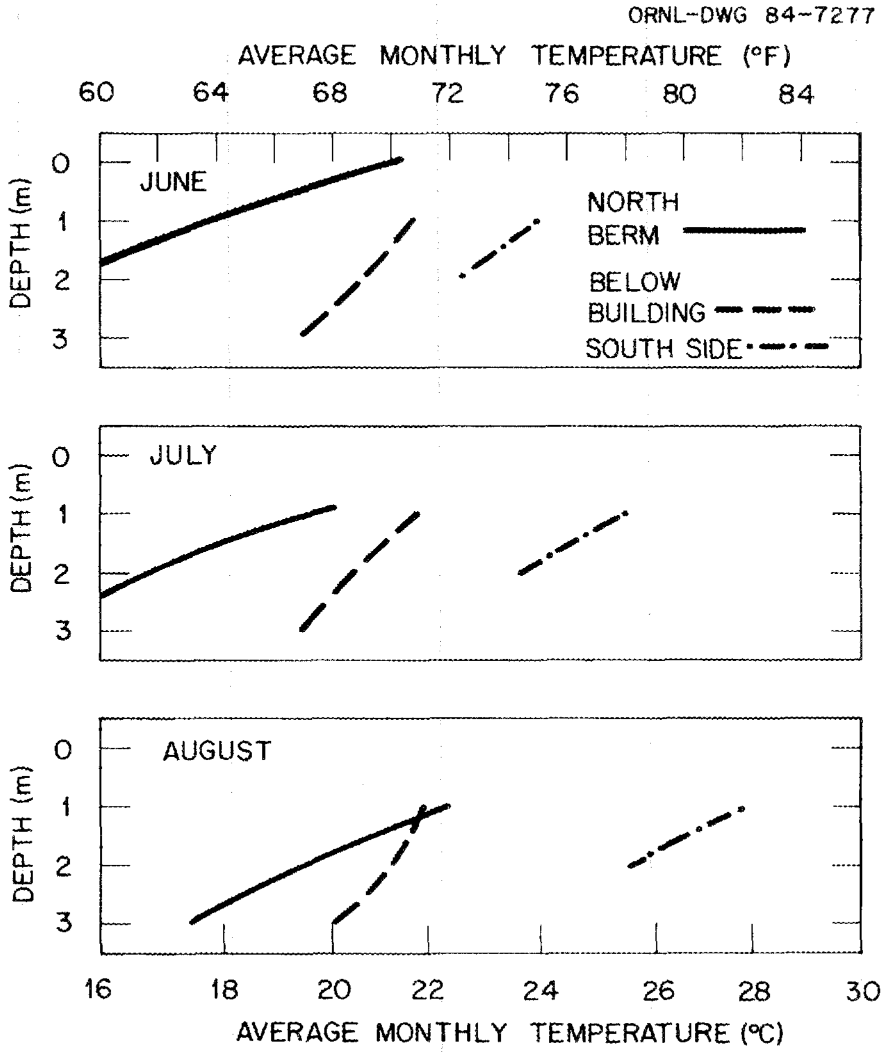

Fig. 5.5. Tautochrones showing earth temperatures as a function of depth at three locations: south side, below, and north side of building.

provides both diurnal thermal storage and a continuous sensible cooling load of approximately 0.4 kWh (1320 Btu/h).

The peak storage occurring at 1600 coincides with the peak daily cooling hour, and the heat is released back to the space at night. The evening ventilation air and occasionally the economizer carry much of this heat out of the space. If the 0.02 m (1 in.) of insulation were not present, even more sensible cooling could be provided by the floor. An estimate, assuming no insulation, suggests the net sensible cooling would triple to about 1.2 kW (3960 Btu/h).

On the average, the floor provides an estimated 11% of the sensible cooling for the building. The presence of 1 in. of insulation penalizes the building in the cooling season. If the floor provided an additional 22% of the sensible cooling, it would reduce the cooling cost by about 24 $/year. However, without insulation, more heat would be lost through the floor in the winter, and the estimated increase would be about $50. Thus, the insulation in the floor at current electric rates of 5.7 ¢/kWh saves about 25 $/year. This accounts for the floor loss only and not for increasing supply duct losses during the winter. Slab floor insulation also provides enhanced thermal comfort in the winter by raising the floor surface temperature and helps prevent condensation in the early summer months when the dew point of the indoor air is above the temperature of the immediately surrounding soil.

This earth-sheltered building is in contact with the earth on three sides, and the soil temperature immediately adjacent to the building envelope varies as a function of envelope component and time. Figure 5.6 shows the average weekly temperatures of the soil adjacent to the floor, roof, and midheight of the bermed walls. For comparison, the ambient air and undisturbed earth temperature at a depth of 5 m are also provided.

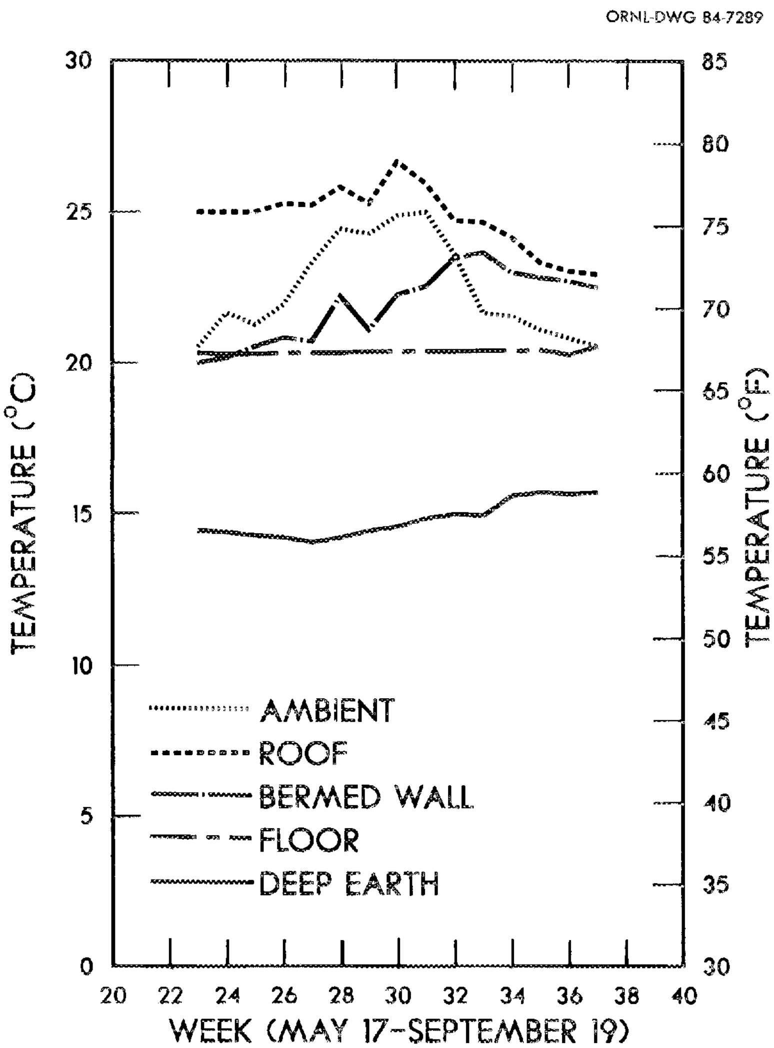

Fig. 5.6. Average weekly soil temperatures surrounding the JID envelope.

5.2 BERMED WALL

Figure 5.6 shows that the average temperature of the north wall between the soil and the wall construction remains below the average ambient air temperature until August. From then to the end of the cooling season, the berm itself does not provide any significant sensible cooling. However, Fig. 5.7 shows that a desirable thermal short exists between the bermed wall and the floor slab. About 18% of the heat going into the wall travels down the wall to the floor slab and eventually into the cooler earth below the building. This was determined by using the average measured temperatures surrounding the north wall to determine the boundary conditions for a finite difference model.[8]

The bermed wall construction consists of a 10-in.-thick poured concrete wall with two ⅝-in. reinforcing rods running vertically on 0.4-m (16-in.) centers, providing a high conductive path between the wall and floor foundation. The wall is fully insulated between the concrete and the earth with 0.08 m (3 in.) of Styrofoam, and the floor slab is insulated with only 0.02 m (1 in.). The insulation helps keep the inside wall surface temperature above the dew-point temperature in early summer when the dew point is about 17°C (62°F). However, more heat could be dissipated to the earth berm with less insulation, especially in the first half of the summer cooling season.

Throughout most of the summer, the bermed wall provides a sensible cooling load of about 0.15 kWh (500 Btu/h). However, in late August, the wall actually contributes a small amount of heat to the building space. No condensation forms on the back wall or on the floor. On the average, the bermed wall provides 5.3% of the sensible cooling provided to the building.

ORNL-DWG 83-7487

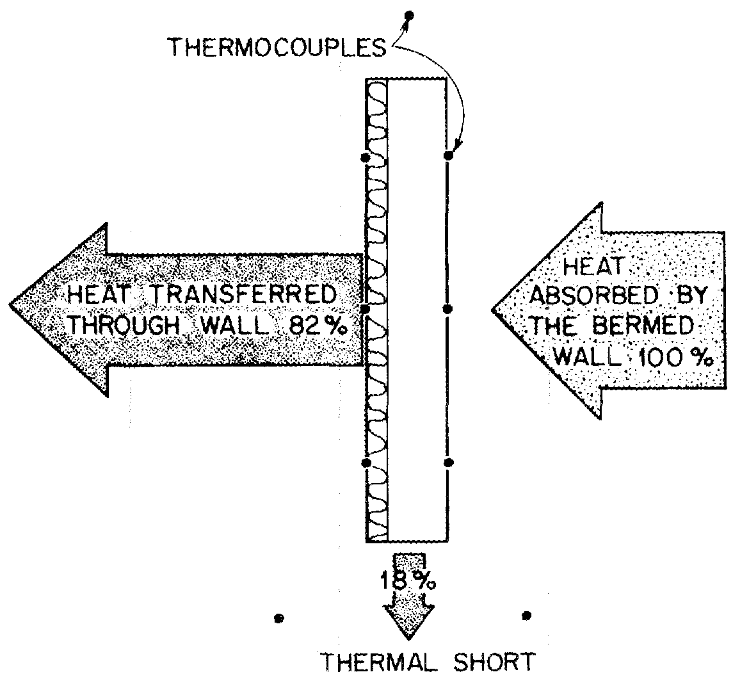

Fig. 5.7. Response factor analysis reveals a desirable thermal short in the bermed wall.

5.3 SOD ROOF

A cross section of the roof construction is shown in Fig. 5.8, along with the location of a number of thermocouples and heat flow sensors. The net heat gain from the roof is very small. In some commercial buildings the roof sensible heat load is the largest single envelope component contribution. Figure 5.9 is a comparison of the measured temperatures taken on the JID roof and a conventional office roof system located in Oak Ridge, Tennessee. The conventional roof system is standard concrete deck with fiberglass insulation board placed on top, covered with a membrane and gravel ballast. The maximum surface temperature above the insulation is 54.4°C (130°F) on the conventional roof compared with 22°C (73°F) just above the insulation in the JID.

Figure 5.8 suggests that the peak heat flux penetrating this roof most likely coincides with the peak cooling load for the entire building. The earth-covered roof system actually supplied a small element of sensible cooling [0.26 kW (900 Btu/h)]. An additional 3.5 kW (1 ton) of cooling capacity would be needed to accommodate the additional heat gain coinciding with the building cooling load coming through a roof with the same R value and without earth covering. On the average, the conventional roof system temperature just above the insulation is 31°C (86°F) in contrast with the JID, which averages about 27°C (80°F) throughout the summer.

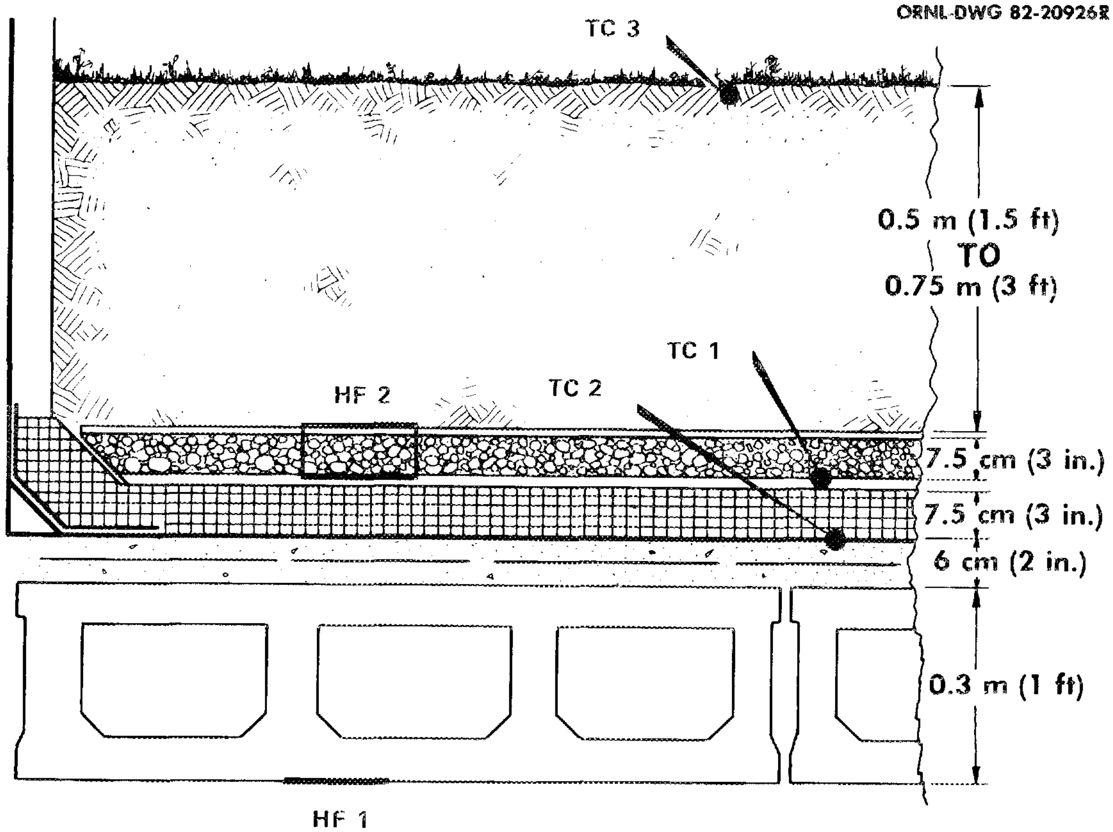

Fig. 5.8. Cross section of the earth-covered roof section.

ORNL-DWG 84-7186

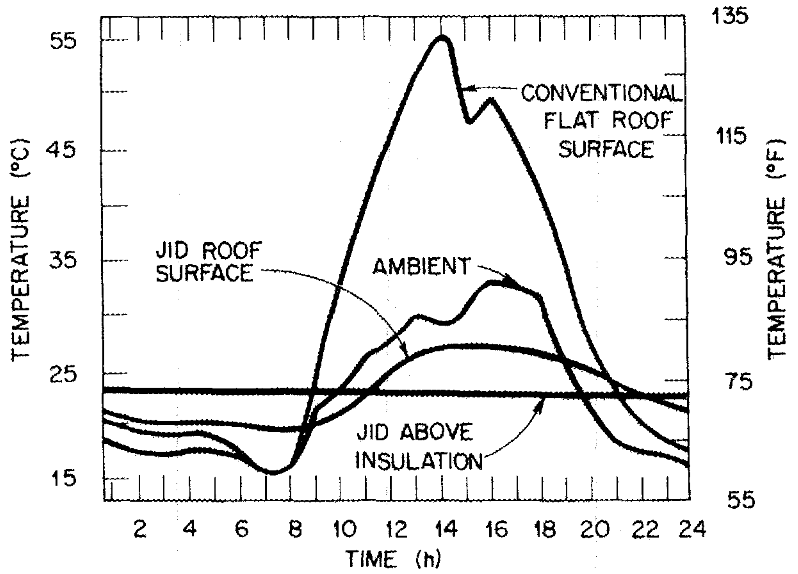

Fig. 5.9. JID roof temperatures compared with those of conventional roof system.

The roof system neutralizes the radiant gain from the sun and results in very little net heat entering the building. The heat that does penetrate the roof system coincides with the early morning hours when the whole-building cooling load is minimal. During the daytime hours, the grass cuts the radiative load, and the soil reduces the roof surface temperature amplitude, resulting in a lower effective temperature difference across the roof.

The effect of the thermal mass capacity of the soil attenuating the temperature fluctuations is apparent. Throughout 1983 the soil was very dry. This had a number of consequences; one was that vegetation did not transpire as much. This is a lost cooling effect. Secondly, the conductivity of the soil remains relatively low, resulting in better insulating capabilities.

6. MAJOR CONCLUSIONS

The JID underground office/dormitory building saves 30 to 50% of the purchased energy needed in well-built above-grade buildings during the cooling season. The cost for space conditioning in this 372-m^2 earth-covered building in a climate typical of Oak Ridge, Tennessee, at 5.7 ¢/kWh is about $300. However, the energy savings over a conventionally built building probably does not justify the incremental cost for underground construction. In spite of the fact that 75% of the south wall contains glass, largely for passive solar heating, extensive thermal comfort measurements show that the JID building does not overheat during the summer months. Peak cooling load is reduced by about one-half because of the extensive thermal mass in and around the building and the extensive shading of the building. Hourly surface temperature recordings gave an indication of the peak energy storage in the building thermal mass.

The JID cooling loads are representative of well-built, energy-efficient structures. Of the energy needed for cooling, 50% is a result of internal electric loads, and 40% comes from sky radiation and ground reflectance through the extensive south-facing windows. The opaque thermal envelope is almost completely neutralized over a diurnal cycle.

The floor and bermed walls provide about 15% of the sensible cooling needed by the building throughout the summer cooling season. The earth-covered roof tracks the average daily temperatures. The high solar radiation loading is completely offset by reflection, vegetative evapotranspiration, and nighttime reradiation to the night sky. What little heat does penetrate this earth-tempered roof system arrives in the interior air during the early morning hours completely out of phase with the building peak cooling loads. The earth-covered roof alone reduces the peak cooling load requirement by at least 25%.

An efficient building envelope and an efficient heat pump do not necessarily produce an optimum whole-building configuration. The coupling between the mechanical equipment and the building must be carefully considered. The location of the heat pump on the west side of the JID, surrounded by a massive retaining wall and the building, penalizes the heat pump performance. The hot afternoon sun creates a hot pocket from which the heat pump must pull air for the condenser coil. A second penalty is the building requirement for continuously circulating air. A fan pulls the circulating air through the single-unit heat pump housing where it picks up a heat load. On mild, sunny afternoons, the heat picked up from the heat pump housing can be higher than all other heat gains to the building. A split heat pump system with the outside coil located on the roof would have been a preferable design. An efficient heat pump installation could reduce the summer cooling cost about 20%. The economizer pulls in outside air for cooling at night when the enthalpy is below the enthalpy of the inside air. In climates with high humidity during the warmer summer months, very little ambient cooling is possible without raising the dew point above recommended conditions. This was the case in the JID; most of the economizer cooling occurred during the beginning and the end of the cooling season, although the seasonal contribution of the economizer amounted to 17% of the total sensible cooling supplied by the heat pump.

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Appendix A

MONTHLY COOLING SEASON SUBMETERED ENERGY DEMAND

Table A.1. Joint Institute Dormitory 1982 summer monthly electric usage (kWh)

	Heat pump[a]	Circulating fan	Water heater	Lights	Kitchen	Other	Total
May	726	297	288	603	96	604	2,317
June	780	288	186	495	60	505	2,026
July	1,340[b]	297	162	633	93	384	2,612
August	1,428	297	447	751	177	601	3,404
September	711	288	189	570	102	425	1,997
Average	997	293	254	610	106	504	2,471
Total	4,985	1,467	1,272	3,052	528	2,519	12,356
Average cost at 5.7 ¢/kWh ($)	57	16	14	35	6	29	141
Total cost at 5.7 ¢/kWh ($)	284	84	72	174	30	144	704

[a]Includes circulating fan.

[b]July 5-12 the building was cooled to 68°F for infrared scan. This required an additional 280 kWh, which was subtracted from actual amount of 1,620 kWh for July.

Table A.2. Joint Institute Dormitory 1983 summer monthly electric usage (kWh)

	Heat pump[a]	Circulating fan	Water heater	Lights	Kitchen	Other	Total
May	297	297	414	478	114	481	1,784
June	711	288	474	508	117	446	2,256
July	1,443	297	354	529	123	488	3,234
August	1,554	297	300	527	153	434	3,264
September	888	288	198	488	108	392	2,074
Average	979	293	348	506	123	448	2,523
Total	4,893	1,467	1,740	2,530	615	2,241	12,613
Average cost at 5.7 ¢/kWh ($)	56	17	20	29	7	26	145
Total cost at 5.7 ¢/kWh ($)	279	84	99	144	35	128	719

[a]Includes circulating fan.

Appendix B

ENERGY BALANCE FOR WEEK 26 (JUNE 21–27)

B.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} \, , \tag{B.1}$$

where

	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

B.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E \, , \tag{B.2}$$

where

M_i	=	submeters (in Eq. B.2, 317.3 kWh),
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. B.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2	=	water heater meter reading for week (43.8 kWh),
ΔT_2	=	temperature difference across water heater tank (35°C in summer),
A_H	=	water heater surface (3 m^2),
U_H	=	thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR	=	hours (168 h).

$$H_L = 0.95[43.8\ \text{kWh} - 35\text{°C} \times 3\ \text{m}^2 \times 0.00081\ \text{kWh}/(\text{m}^2 \cdot \text{°C}) \times 168\ \text{h}] = 28\ \text{kWh}\ .$$

L_O (outside lights):

$$L_O = OL \times HR_D\ ,$$

where

OL	=	wattage of outside lights (0.44 kW),
HR_D	=	hours of darkness (79 h).

$$L_O = 0.44\ \text{kW} \times 79\ \text{h} = 34.7\ \text{kWh}\ .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF \times HR_{OF})\ ,$$

where

SH	=	sensible heat per person per hour (0.073 kWh),
BD	=	number of beds occupied for energy balance period (21),
HR_{BD}	=	number of hours per day an overnight occupant spends in building (14 h),
OF	=	number of offices occupied for period of study (15),
HR_{OF}	=	number of hours per day that a daytime occupant spends in building (6 h).

$$P_E = 0.073\ \text{kWh} \times (21 \times 14\ \text{h} + 15 \times 6\ \text{h}) = 28\ \text{kWh}\ .$$

B_F (restroom fan):

$$B_F = BP \times HR_O ,$$

where

BP = restroom fan power (0.2 kW),
HR_O = number of hours restroom exhaust fan is on (168 h),

$$B_F = 0.2 \text{ kW} \times 168 \text{ h} = 33.6 \text{ kWh} .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K ,$$

where

KF = kitchen fan power (0.2 kW),
HR_K = length of time kitchen fan is on (0.0 h),

$$K_F = 0.2 \text{ kW} \times 0.0 \text{ h} = 0 \text{ kWh} .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i ,$$

where

M_o = master meter (482 kWh),
M_i = submeters (469 kWh).

$$A_E = (482 \text{ kWh} - 469 \text{ kWh}) = 13 \text{ kWh} .$$

$$IL = 317.3 - 43.8 - 34.7 + 28 - 33.6 - 0 + 13 = 246.2 \text{ kWh} .$$

B.1.2 South-Facing Windows (SW)

$$SW = \sum_{i=1}^{3} A_i(L_i \times SC_i - u_i \times \Delta T_i \times h) ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study ($L_{1,2,3} = 6.25$ kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5,
u_i	=	thermal transmittance [0.00203 $kW/(m^2 \cdot °C)$],
ΔT_i	=	temperature difference between inside and outside air (2.2°C),
h	=	hours.

$$SW = 30\ m^2 \times (6.25\ kWh/m^2 \times 0.75 - 0.00203 \times 2.2°C \times 168\ h)$$
$$+ 13\ m^2 \times (6.25\ kWh/m^2 \times 0.67 - 0.00203 \times 2.2°C \times 168\ h)$$
$$+ 16.5\ m^2 \times (6.25\ kWh/m^2 \times 0.5 - 0.00203 \times 2.2°C \times 168\ h) = 202\ kWh\ .$$

B.1.3 Trombe Wall (TR)

$$TR = Q_T \times A_T\ ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (−0.075 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2).

$$TR = 0.075\ kWh/m^2 \times 12.3\ m^2 = 0.9\ kWh\ .$$

B.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR\ ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 $kWh/(m^2 \cdot °C)$],
$CLTD_N$	=	adjusted cooling load temperature difference from ASHRAE Ch. 26, Table 7 (2.1°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004\ kWh/(m^2 \cdot °C) \times 2.1°C \times 22\ m^2 \times 168\ h = 3.1\ kWh\ .$$

B.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR \ ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m²·°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (6.0°C),
A_{EW}	=	east wall area (9.5 m²).

$$W_E = 0.0004 \text{ kWh/(m}^2\cdot{}^\circ\text{C)} \times 6.0^\circ\text{C} \times 9.5 \text{ m}^2 \times 168 \text{ h} = 3.8 \text{ kWh} \ .$$

B.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR \ ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m²·°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (6.0°C),
A_{WW}	=	west wall area (25.3 m²).

$$W_W = 0.0004 \text{ kWh/(m}^2\cdot{}^\circ\text{C)} \times 6.0^\circ\text{C} \times 25.3 \times 168 \text{ h} = 10.2 \text{ kWh} \ .$$

B.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR \ ,$$

where

SC_E	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.678 kWh/m²),
CLF_E	=	cooling load factor (0.24),
A_E	=	east window area (0.56 m²).

$$EW = 0.88 \times 0.678 \text{ kWh/m}^2 \times 0.24 \times 0.56 \text{ m}^2 \times 35 \text{ h} = 2.8 \text{ kWh} \ .$$

B.1.8 West Window (WW)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR ,$$

where

SC_W	=	shading coefficient (0.88),
$MSGH_W$	=	maximum solar heat gain (0.678 kWh/m^2),
CLF_W	=	cooling load factor (0.32),
A_W	=	west window area (0.56 m^2).

$$WW = 0.88 \times 0.678 \text{ kWh/m}^2 \times 0.32 \times 0.56 \text{ m}^2 \times 35 \text{ h} = 3.7 \text{ kWh} .$$

B.1.9 Roof (R)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation in the roof (0.0004 kWh/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation in the roof (0.00028 kWh/m^2),
A_R	=	roof area (372 m^2).

$$R = (0.5 \times 0.0004 \text{ kWh/m}^2 + 0.5 \times 0.00028 \text{ kWh/m}^2) \times 372 \text{ m}^2 \times 168 \text{ h} = 21.2 \text{ kWh} .$$

B.1.10 Infiltration and Ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7\ HR_O + 0.5\ HR_F) ,$$

where

ΔT	=	average temperature difference between inside and outside air (−1.16°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (168 h),
HR_F	=	hours with restroom exhaust fan off (0 h).

$$Q_{VI} = -1.16°\text{C} \times 0.343 \times 920 \text{ m}^3 \times (0.7 \times 168 \text{ h} + 0.5 \times 0 \text{ h}) = -43 \text{ kWh} .$$

B.2 BUILDING SENSIBLE THERMAL LOSSES

B.2.1 Heat Pump (Q_H)

$$Q_H = \sum_{i=1}^{HR} (Q_L) = 143 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by DAS each hour cooling is called for (kW).

B.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR \times CF_N ,$$

where

Q_{NW} = average inside heat flow sensor (-0.00273 kW/m^2),
A_W = bermed wall area (114 m^2),
CF_N = correction factor to account for more representative location of heat flow sensor on wall (1.0).

$$W_N = -0.00273 \text{ kW/m}^2 \times 114 \text{ m}^2 \times 168 \text{ h} \times 1.0 = -52 \text{ kWh} .$$

B.2.3 Floor (W_F)

$$W_F = Q_F \times A_F \times HR ,$$

where

Q_F = average heat flow from front and back floor sensors (-0.00126 kWh/m^2),
A_F = floor area (372 m^2).

$$W_F = -0.00126 \text{ kWh/m}^2 \times 372 \text{ m}^2 \times 168 \text{ h} = -78.7 \text{ kWh} .$$

B.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = 114.5 ,$$

where

Q_{HE}	=	amount of sensible cooling measured by DAS from economizer,
HR_E	=	hours with economizer damper open.

Table B.1. Week 26 summary

Heat gains		Heat losses	
Source	kWh	Source	kWh
Internal loads	246.2	Heat pump	143.0
Windows		Bermed walls	52.0
South	202.0		
East	2.8	Floor	78.7
West	3.7		
Trombe	−0.9	Economizer	114.0
Outside walls			
South	3.1		
East	3.8		
West	10.2		
Roof	21.2		
Infiltration and ventilation	−43.0		
Total	449.1		387.7

Appendix C

ENERGY BALANCE FOR WEEK 27 (June 28–July 4)

C.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} \; , \tag{C.1}$$

where

G	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

C.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E \; , \tag{C.2}$$

where

M_i	=	submeters (in Eq. C.2, 247 kWh),
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. C.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2	=	water heater meter reading for week (26.6 kWh),
ΔT_2	=	temperature difference across water heater tank (35°C in summer),
A_H	=	water heater surface (3 m^2),
U_H	=	thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR	=	hours (168 h).

$$H_L = 0.95[26.6 \text{ kWh} - 35°\text{C} \times 3 \text{ m}^2 \times 0.00081 \text{ kWh/(m}^2 \cdot °\text{C)} \times 168 \text{ h}] = 11.7 \text{ kWh} .$$

L_O (outside lights):

$$L_O = OL \times HR_D ,$$

where

OL	=	wattage of outside lights (0.44 kW),
HR_D	=	hours of darkness (77 h).

$$L_O = 0.44 \text{ kW} \times 77 \text{ h} = 34 \text{ kWh} .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF \times HR_{OF}) ,$$

where

SH	=	sensible heat per person per hour (0.073 kWh),
BD	=	number of beds occupied for energy balance period,
HR_{BD}	=	number of hours per day an overnight occupant spends in building,
OF	=	number of offices occupied for period of study,
HR_{OF}	=	number of hours per day that a daytime occupant spends in building.

$$P_E = 0.073 \text{ kWh} \times (12 \times 14 \text{ h} + 15 \times 6 \text{ h}) = 18.8 \text{ kWh} .$$

B_F (restroom fan):

$$B_F = BP \times HR_O \ ,$$

where

BP	=	restroom fan power (0.2 kW),
HR_O	=	number of hours restroom exhaust fan is on (168 h).

$$B_F = 0.2 \text{ kW} \times 168 \text{ h} = 33.6 \text{ kWh} \ .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K \ ,$$

where

KF	=	kitchen fan power (0.2 kW),
HR_K	=	length of time kitchen fan is on (0.0 h).

$$K_F = 0.2 \text{ kW} \times 0.0 \text{ h} = 0 \text{ kWh} \ .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i \ ,$$

where

M_o	=	master meter (295 kWh),
M_i	=	submeters (282 kWh),

$$A_E = (295 - 282) = 13 \text{ kWh} \ .$$

$$IL = 247 - 11.7 - 34 + 18.8 - 33.6 - 0 + 13 = 199.5 \text{ kWh} \ .$$

C.1.2 South-Facing Windows (*SW*)

$$SW = \sum_{i=1}^{3} A_i(L_i \times SC_i - u_i \times \Delta T_i \times h) \ ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study ($L_{1,2,3,} = 6.1$ kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5,
u_i	=	thermal transmittance [0.00203 kW/($m^2 \cdot$°C)],
ΔT_i	=	temperature difference between inside and outside air (0.6°C),
h	=	hours.

$$SW = 30\ \mathrm{m^2} \times 6.1\ \mathrm{kWh/(m^2 \cdot °C)} \times 0.75 + 13\ \mathrm{m^2} \times 6.1\ \mathrm{kWh/(m^2 \cdot °C)} \times 0.67$$
$$+ 16.5\ \mathrm{m^2} \times 6.1\ \mathrm{kWh/m^2} \times 0.5$$
$$- 0.00203\ \mathrm{kWh/(m^2 \cdot °C)} \times 59.5\ \mathrm{m^2} \times 168\ \mathrm{h} \times 0.6\mathrm{°C} = 228.4\ \mathrm{kWh}\ .$$

C.1.3 Trombe Wall (*TR*)

$$TR = Q_T \times A_T\ ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (0.06 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2),

$$TR = 0.06\ \mathrm{kWh/m^2} \times 12.3\ \mathrm{m^2} = 0.74\ \mathrm{kWh}\ .$$

C.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR\ ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kW/($m^2 \cdot$°C)],
$CLTD_N$	=	adjusted cooling load temperature difference from ASHRAE Ch. 26, Table 7 (2.1°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004\ \mathrm{kW/(m^2 \cdot °C)} \times 2.1\mathrm{°C} \times 22\ \mathrm{m^2} \times 168\ \mathrm{h} = 3.105\ \mathrm{kWh}\ .$$

C.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR \ ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 W/(m$^2\cdot$°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (6°C),
A_{EW}	=	east wall area (9.5 m^2).

$$W_E = 0.0004 \ \mathrm{W/(m^2 \cdot {}^\circ C)} \times 6^\circ\mathrm{C} \times 9.5 \ \mathrm{m^2} \times 168 \ \mathrm{h} = 3.8 \ \mathrm{kWh} \ .$$

C.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR \ ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 W/(m$^2\cdot$°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (6°C),
A_{WW}	=	west wall area (25.3 m^2).

$$W_W = 0.0004 \ \mathrm{W/(m^2 \cdot {}^\circ C)} \times 6^\circ\mathrm{C} \times 25.3 \ \mathrm{m^2} \times 168 \ \mathrm{h} = 10.2 \ \mathrm{kWh} \ .$$

C.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR \ ,$$

where

SC_E	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.678 kWh/m^2),
CLF_E	=	cooling load factor (0.24),
A_E	=	east window area.

$$EW = 0.88 \times 0.678 \ \mathrm{kWh/m^2} \times 0.24 \times 0.56 \ \mathrm{m^2} \times 35 \ \mathrm{h} = 2.8 \ \mathrm{kWh} \ .$$

C.1.8 West Window (*WW*)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR \ ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_W$	=	maximum solar heat gain (0.678 kWh/m^2),
CLF_W	=	cooling load factor (0.32),
A_W	=	west window area (0.56 m^2).

$$WW = (0.88 \times 0.678 \text{ kWh/m}^2 \times 0.32 \times 0.56 \text{ m}^2 \times 35 \text{ h}) = 3.7 \text{ kWh} \ .$$

C.1.9 Roof (*R*)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR \ ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation (0.0005 kW/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation (0.00028 kW/m^2),
A_R	=	roof area (372 m^2).

$$R = (0.5 \times 0.0005 \text{ kW/m}^2 + 0.5 \times 0.00028 \text{ kW/m}^2) \times 372 \text{ m}^2 \times 168 \text{ h} = 24.4 \text{ kWh} \ .$$

C.1.10 Infiltration and ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7 \times HR_O + 0.5 \times HR_F) \ ,$$

where

ΔT	=	average temperature difference between inside and outside air (0.7°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (168 h),
HR_F	=	hours with restroom exhaust fan off (0 h) .

$$Q_{VI} = 0.7°\text{C} \times 0.343 \times 920 \text{ m}^3 \times (0.7 \times 168 \text{ h} + 0.5 \times 0 \text{ h}) = 26 \text{ kWh} \ .$$

C.2 BUILDING SENSIBLE THERMAL LOSSES

C.2.1 Heat Pump (Q_H)

$$Q_H = \sum_{L=1}^{168} (Q_L) = 150 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by data logger each hour cooling is called for.

C.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR = 38.7 \text{ kWh} ,$$

where

Q_{NW} = average inside heat flow measurement (-2.02 W/m^2),
A_W = bermed wall area (114 m^2).

C.2.3 Floor

$$W_F = Q_F \times A_F \times HR = 93.1 \text{ W/m}^2 ,$$

where

Q_F = average heat flow from front and back floor sensors (-0.00149 kW/m^2),
A_F = floor area (372 m^2).

C.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = 76 .$$

where

Q_{HE} = sensible cooling delivered,
HR_E = hours with economizer damper open.

Table C.1. Week 27 summary

Heat gains		Heat losses	
Source	kWh	Source	kWh
Internal loads	199.5	Heat pump	150.0
Windows		Bermed walls	38.7
South	228.4		
East	2.8	Floor	93.1
West	3.7		
Trombe	0.7	Economizer	76.0
Outside walls			
South	3.1		
East	3.8		
West	10.2		
Roof	24.4		
Infiltration and ventilation	26.0		
Total	502.6		357.8

Appendix D

ENERGY BALANCE FOR WEEK 33 (AUGUST 9–15)

D.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} \ , \qquad \text{(D.1)}$$

where

G	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

D.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E \ , \qquad \text{(D.2)}$$

where

M_i	=	submeters [in Eq. D.2, 360.3 kWh],
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. D.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2	=	water heater meter reading for week (114 kWh),
ΔT_2	=	temperature difference across water heater tank (35°C in summer),
A_H	=	water heater surface area (3 m^2),
U_H	=	thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR	=	hours (168 h).

$$H_L = 0.95[114 \text{ kWh} - 35°\text{C} \times 3 \text{ m}^2 \times 0.00081 \text{ kWh}/(\text{m}^2 \cdot °\text{C}) \times 168 \text{ h}] = 95 \text{ kWh} .$$

L_O (outside lights):

$$L_O = OL \times HR_D ,$$

where

OL	=	wattage of outside lights (0.44 kW),
HR_D	=	hours of darkness (85 h).

$$L_O = 0.44 \text{ kW} \times 85 \text{ h} = 37.4 \text{ kWh} .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF \times HR_{OF}) ,$$

where

SH	=	sensible heat per person per hour (0.073 kWh),
BD	=	number of beds occupied for energy balance period (34),
HR_{BD}	=	number of hours per day an overnight occupant spends in building (14 h),
OF	=	number of offices occupied for period of study (15),
HR_{OF}	=	number of hours per day that a daytime occupant spends in building (6 h).

$$P_E = 0.073 \text{ kWh} \times (34 \times 14 \text{ h} + 15 \times 6 \text{ h}) = 41 \text{ kWh} .$$

B_F (restroom fan):

$$B_F = BP \times HR_O ,$$

where

BP = restroom fan power (0.2 kW),
HR_O = number of hours restroom exhaust fan is on (166 h).

$$B_F = 0.2 \text{ kW} \times 166 \text{ h} = 33.2 \text{ kWh} .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K ,$$

where

KF = kitchen fan power (0.2 kW),
HR_K = length of time kitchen fan is on (0.0 h).

$$K_F = 0.2 \text{ kW} \times 0.0 \text{ h} = 0 \text{ kWh} .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i ,$$

where

M_o = master meter (779 kWh),
M_i = submeters (750 kWh).

$$A_E = (779 - 750) = 29 \text{ kWh} .$$

$$IL = 360.3 - 95 - 37.4 + 41 - 33.2 - 0 + 29 = 264.7 \text{ kWh} .$$

D.1.2 South-Facing Windows (*SW*)

$$SW = \sum_{i=1}^{3} A_i(L_i \times SC_i - u_i \times \Delta T_i \times HR) ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study ($L_{1,2,3} = 6.8$ kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5,
u_i	=	thermal transmittance [0.00203 kW/($m^2\cdot$°C)],
ΔT_i	=	temperature difference between inside and outside air (1.1°C),
HR	=	hours.

$$\begin{aligned} SW = {} & 30\ \text{m}^2 \times 6.8\ \text{kWh/m}^2 \times 0.75 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 1.1^\circ\text{C} \times 168\ \text{h} \\ & + 13(6.8\ \text{kWh/m}^2 \times 0.67 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 1.1^\circ\text{C} \times 168\ \text{h}) \\ & + 16.5[6.8\ \text{kWh/m}^2 \times 0.5 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 1.1^\circ\text{C} \times 168\ \text{h}] = 243.3\ \text{kWh}\ . \end{aligned}$$

D.1.3 Trombe Wall (TR)

$$TR = Q_T \times A_T\ ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (0.137 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2).

$$TR = 0.137\ \text{kWh/m}^2 \times 12.3\ \text{m}^2 = 1.7\ \text{kWh}\ .$$

D.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR\ ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/($m^2\cdot$°C)],
$CLTD_N$	=	adjusted cooling load temperature difference from ASHRAE Ch. 26, Table 7 (0.4°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 0.4^\circ\text{C} \times 22\ \text{m}^2 \times 168\ \text{h} = 0.6\ \text{kWh}\ .$$

D.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR \ ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2\cdot$°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (5.6°C),
A_{EW}	=	east wall area (9.5 m^2).

$$W_E = 0.0004 \times 5.6°\mathrm{C} \times 9.5 \ \mathrm{m}^2 \times 168 \ \mathrm{h} = 3.6 \ \mathrm{kWh} \ .$$

D.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR \ ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2\cdot$°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (5.1°C),
A_{WW}	=	west wall area (25.3 m^2).

$$W_W = 0.0004 \ \mathrm{kWh/(m^2\cdot°C)} \times 5.1°\mathrm{C} \times 25.3 \ \mathrm{m}^2 \times 168 \ \mathrm{h} = 8.7 \ \mathrm{kWh} \ .$$

D.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR \ ,$$

where

SC_E	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.68 kWh/m^2),
CLF_E	=	cooling load factor (0.3),
A_E	=	east window area (0.56 m^2).

$$EW = 0.88 \times 0.68 \ \mathrm{kWh/m^2} \times 0.3 \times 0.56 \ \mathrm{m}^2 \times 35 \ \mathrm{h} = 3.5 \ \mathrm{kWh} \ .$$

D.1.8 West Window (*WW*)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR \ ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_W$	=	maximum solar heat gain (0.51 kWh/m^2),
CLF_W	=	cooling load factor (0.3),
A_W	=	west window area (0.56 m^2).

$$WW = 0.88 \times 0.51 \ \text{kWh/m}^2 \times 0.3 \times 0.56 \ \text{m}^2 \times 35 \ \text{h} = 2.6 \ \text{kWh} \ .$$

D.1.9 Roof (*R*)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR \ ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation (0.00022 kWh/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation (0.00016 kWh/m^2),
A_R	=	roof area (372 m^2).

$$R = (0.5 \times 0.00022 \ \text{kWh/m}^2 + 0.5 \times 0.00016 \ \text{kWh/m}^2) \\ \times 372 \ \text{m}^2 \times 168 \ \text{h} = 11.9 \ \text{kWh} \ .$$

D.1.10 Infiltration and ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7 \ HR_O + 0.5 \ HR_F) \ ,$$

where

ΔT	=	average temperature difference between inside and outside air (0.0°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (166 h),
HR_F	=	hours with restroom exhaust fan off (0 h) .

$$Q_{VI} = 0.0°\text{C} \times 0.343 \times 920 \ \text{m}^3 \times (0.7 \times 166 \ \text{h} + 0.5 \times 0 \ \text{h}) = 0 \ \text{kWh} \ .$$

D.2 BUILDING SENSIBLE THERMAL LOSSES

D.2.1 Heat Pump (Q_H)

$$Q_H = \sum_{i=1}^{HR} (Q_L) = 560 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by DAS each hour cooling is called for (kW).

D.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR \times CF_N ,$$

where

Q_{NW} = average inside heat flow sensor (0.000337 kW/m^2),
A_W = bermed wall area (114 m^2),
CF_N = correction factor to account for more representative location of heat flow sensor on wall (1.0).

$$W_N = 0.000337 \text{ kW/m}^2 \times 114 \text{ m}^2 \times 168 \text{ h} \times 1.0 = 6.5 \text{ kWh} .$$

D.2.3 Floor

$$W_F = Q_F \times A_F \times HR ,$$

where

Q_F = average heat flow from front and back floor sensors (0.0007 kWh/m^2),
A_F = floor area (372 m^2).

$$W_F = 0.0007 \text{ kWh/m}^2 \times 372 \text{ m}^2 \times 168 \text{ h} = 43.7 \text{ kWh} .$$

D.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = 0 ,$$

where

Q_{HE} = amount of sensible cooling measured by DAS from economizer,

HR_E = hours in which the economizer damper is open.

Table D.1. Week 33 summary

Heat gains		Heat losses	
Source	kWh	Source	kWh
Internal loads	264.7	Heat pump	560.0
Windows		Bermed walls	6.5
South	243.3		
East	3.5	Floor	43.7
West	2.6		
Trombe	1.7	Economizer	0
Outside walls			
South	0.6		
East	3.6		
West	8.7		
Roof	11.9		
Infiltration and ventilation	0		
Total	540.6		610.2

Appendix E

ENERGY BALANCE FOR WEEK 34 (AUGUST 16–22)

E.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} \ , \tag{E.1}$$

where

G	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

E.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E \ , \tag{E.2}$$

where

M_i	=	submeters [in Eq. E.2, 511 kWh],
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. E.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2 = water heater meter reading for week (150 kWh),
ΔT_2 = temperature difference across water heater tank (35°C in summer),
A_H = water heater surface (3 m^2),
U_H = thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR = hours (168 h).

$$H_L = 0.95[150 \text{ kWh} - 35\text{°C} \times 3 \text{ m}^2 \times 0.00081 \text{ kWh/(m}^2\cdot\text{°C)} \times 168 \text{ h}] = 129 \text{ kWh} .$$

L_O (outside lights):

$$L_O = OL \times HR_D ,$$

where

OL = wattage of outside lights (0.44 kW),
HR_D = hours of darkness (86 h).

$$L_O = 0.44 \text{ kW} \times 86 \text{ h} = 38 \text{ kWh} .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF \times HR_{OF}) ,$$

where

SH = sensible heat per person per hour (0.073 kWh),
BD = number of beds occupied for energy balance period (45),
HR_{BD} = number of hours per day an overnight occupant spends in building (14 h),
OF = number of offices occupied for period of study (17),
HR_{OF} = number of hours per day that a daytime occupant spends in building (6 h).

$$P_E = 0.073 \text{ kWh} \times (45 \times 14 \text{ h} + 17 \times 6 \text{ h}) = 53.4 \text{ kWh} .$$

B_F (restroom fan):

$$B_F = BP \times HR_O ,$$

where

BP	=	restroom fan power (0.2 kW),
HR_O	=	number of hours restroom exhaust fan is on (162 h).

$$B_F = 0.2 \text{ kW} \times 162 \text{ h} = 32.4 \text{ kWh} .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K ,$$

where

KF	=	kitchen fan power (0.2 kW),
HR_K	=	length of time kitchen fan is on (11 h).

$$K_F = 0.2 \text{ kW} \times 11 \text{ h} = 2.2 \text{ kWh} .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i ,$$

where

M_o	=	master meter (786.1 kWh),
M_i	=	submeters (757.1 kWh).

$$A_E = (786.1 - 757.1) = 29 \text{ kWh} .$$

$$IL = 511 - 129 - 38 + 53.4 - 32.4 - 2.2 + 29 = 391.8 \text{ kWh}$$

E.1.2 South-Facing Windows (*SW*)

$$SW = \sum_{i=1}^{3} A_i(L_i \times SC_i - u_i \times \Delta T_i \times HR) ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study ($L_{1,2,3} = 6.2$ kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5,
u_i	=	thermal transmittance [0.00203 kW/($m^2 \cdot$°C)],
ΔT_i	=	temperature difference between inside and outside air (−2.2°C).

$$SW = 30\ \text{m}^2 \times (6.2\ \text{kWh/m}^2 \times 0.75 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 2.2^\circ\text{C} \times 168\ \text{h})$$
$$+\ 13\ \text{m}^2 \times (6.2\ \text{kWh/m}^2 \times 0.67 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 2.2^\circ\text{C} \times 168\ \text{h})$$
$$+\ 16.5\ \text{m}^2 \times [6.2\ \text{kW/m}^2 \times 0.5 - 0.00203\ \text{kW/(m}^2\cdot{}^\circ\text{C)} \times 2.2^\circ\text{C} \times 168\ \text{h}] = 200\ \text{kWh}\ .$$

E.1.3 Trombe Wall (*TR*)

$$TR = Q_T \times A_T\ ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (0.73 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2).

$$TR = 0.73\ \text{kWh/m}^2 \times 12.3\ \text{m}^2 = 9\ \text{kWh}\ .$$

E.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR\ ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/($m^2 \cdot$°C)],
$CLTD_N$	=	adjusted cooling load temperature difference ASHRAE Ch. 26, Table 7 (0.5°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004\ \text{kW/m}^2 \times 0.5^\circ\text{C} \times 22\ \text{m}^2 \times 168\ \text{h} = 0.7\ \text{kWh}\ .$$

E.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m^2·°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (5.7°C),
A_{EW}	=	east wall area (9.5 m^2).

$$W_E = 0.0004 \text{ kWh/(m}^2\text{·°C)} \times 5.7\text{°C} \times 9.5 \text{ m}^2 \times 168 \text{ h} = 3.6 \text{ kWh} .$$

E.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m^2·°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (5.2°C),
A_{WW}	=	west wall area (25.3 m^2).

$$W_W = 0.0004 \text{ kWh/(m}^2\text{·°C)} \times 5.2\text{°C} \times 25.3 \text{ m}^2 \times 168 \text{ h} = 8.8 \text{ kWh} .$$

E.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR ,$$

where

SC_E	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.68 kWh/m^2),
CLF_E	=	cooling load factor (0.3),
A_E	=	east window area (0.56 m^2).

$$EW = 0.88 \times 0.68 \text{ kWh/m}^2 \times 0.3 \times 0.56 \text{ m}^2 \times 35 \text{ h} = 3.5 \text{ kWh} .$$

E.1.8 West Window (WW)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR \ ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_W$	=	maximum solar heat gain (0.51 kWh/m^2),
CLF_W	=	cooling load factor (0.3),
A_W	=	west window area (0.56 m^2).

$$WW = 0.88 \times 0.51 \text{ kWh/m}^2 \times 0.3 \times 0.56 \text{ m}^2 \times 35 \text{ h} = 2.6 \text{ kWh} \ .$$

E.1.9 Roof (R)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR \ ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation (0.00015 kWh/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation (0.00003 kWh/m^2),
A_R	=	roof area (372 m^2).

$$R = (0.5 \times 0.00015 \text{ kWh/m}^2 + 0.5 \times 0.00003 \text{ kWh/m}^2) \times 372 \text{ m}^2 \times 168 \text{ h} = 5.6 \text{ kWh} \ .$$

E.1.10 Infiltration and ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7 \times HR_O + 0.5 \times HR_F) \ ,$$

where

ΔT	=	average temperature difference between inside and outside air (-0.6°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (162 h),
HR_F	=	hours with restroom exhaust fan off (6 h).

$$Q_{VI} = -0.6\text{°C} \times 0.343 \times 920 \text{ m}^3 \times (0.7 \times 162 \text{ h} + 0.5 \times 6 \text{ h}) = -22 \text{ kWh} \ .$$

E.2 BUILDING SENSIBLE THERMAL LOSSES

E.2.1 HEAT PUMP (Q_H)

$$Q_H = \sum_{i=1}^{HR} Q_L = 337 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by DAS each hour cooling is called for (kW).

E.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR \times CF_N ,$$

where

Q_{NW} = average inside heat flow sensor (-0.00161 kW/m^2),
A_W = bermed wall area (114 m^2),
CF_N = correction factor to account for more representative location of heat flow sensor on wall (1.0).

$$W_N = -0.00161 \text{ kW/m}^2 \times 114 \text{ m}^2 \times 168 \text{ h} \times 1.0 = -30.8 \text{ kWh} .$$

E.2.3 Floor (W_F)

$$W_F = Q_F \times A_F \times HR ,$$

where

Q_F = average heat flow from front and back floor sensors (-0.000945 kWh/m^2),
A_F = floor area (372 m^2).

$$W_F = -0.000945 \text{ kWh/m}^2 \times 372 \text{ m}^2 \times 168 \text{ h} = -59 \text{ kWh} .$$

E.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = -33.5 ,$$

where

Q_{HE} = amount of sensible cooling measured by DAS from economizer,

HR_E = hours in which the economizer damper is open.

Table E.1. Week 34 summary

Heat Gains		Heat Losses	
Source	kWh	Source	kWh
Internal loads	391.8	Heat pump	337.0
Windows		Bermed walls	30.8
South	200.0		
East	3.5	Floor	59.0
West	2.6		
Trombe	9.0	Economizer	33.5
Outside walls			
South	0.7		
East	3.6		
West	8.8		
Roof	5.6		
Infiltration and ventilation	−22.0		
Total	603.6		460.3

Appendix F

ENERGY BALANCE FOR WEEK 35 (AUGUST 23–29)

F.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} \,, \qquad \text{(F.1)}$$

where

G	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

F.1.1 Internal Loads (IL)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E \,, \qquad \text{(F.2)}$$

where

M_i	=	submeters (in Eq. F.2, 339.8 kWh),
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. F.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2	=	water heater meter reading for week (63 kWh),
ΔT_2	=	temperature difference across water heater tank (35°C in summer),
A_H	=	water heater surface (3 m^2),
U_H	=	thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR	=	hours (168 h).

$$H_L = 0.95[63 \text{ kWh} - 35\text{°C} \times 3 \text{ m}^2 \times 0.00081 \text{ kWh/(m}^2\cdot\text{°C)} \times 168 \text{ h}] = 46.3 \text{ kWh} .$$

L_O (outside lights):

$$L_O = OL \times HR_D ,$$

where

OL	=	wattage of outside lights (0.44 kW),
HR_D	=	hours of darkness (88 h).

$$L_O = 0.44 \text{ kW} \times 88 \text{ h} = 38.7 \text{ kWh} .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF \times HR_{OF}) ,$$

where

SH	=	sensible heat per person per hour (0.073 kWh),
BD	=	number of beds occupied for energy balance period (35),
HR_{BD}	=	number of hours per day an overnight occupant spends in building (14 h),
OF	=	number of offices occupied for period of study (16),
HR_{OF}	=	number of hours per day that a daytime occupant spends in building (6 h).

$$P_E = 0.073 \text{ kWh} \times (35 \times 14 \text{ h} + 16 \times 6 \text{ h}) = 42.8 \text{ kWh} .$$

B_F (restroom fan):

$$B_F = BP \times HR_O ,$$

where

BP	=	restroom fan power (0.2 kW),
HR_O	=	number of hours restroom exhaust fan is on (145 h),

$$B_F = 0.2 \text{ kW} \times 145 \text{ h} = 29 \text{ kWh} .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K ,$$

where

KF	=	kitchen fan power (0.2 kW),
HR_K	=	length of time kitchen fan is on (0 h).

$$K_F = 0.2 \text{ kW} \times 0 \text{ h} = 0 \text{ kWh} .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i ,$$

where

M_o	=	master meter (623.6 kWh),
M_i	=	submeters (594.6 kWh),

$$A_E = (623.6 - 594.6) = 29 \text{ kWh} .$$

$$IL = 339.8 - 46.3 - 38.7 + 42.8 - 29 - 0 + 29 = 297.6 \text{ kWh} .$$

F.1.2 South-Facing Windows (SW)

$$SW = \sum_{i=1}^{3} A_i(L_i \times SC_i - u_i \times \Delta T_i \times HR) ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study ($L_{1,2,3}$ = 7.47 kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5,
u_i	=	thermal transmittance [0.00203 $kW/(m^2 \cdot °C)$],
ΔT_i	=	temperature difference between inside and outside air (2.1°C),
HR	=	hours.

$$SW = 30 \text{ m}^2 \times [7.47 \text{ kWh/m}^2 \times 0.75 - 0.00203 \text{ kW/(m}^2\cdot°\text{C)} \times 2.1°\text{C} \times 168 \text{ h}]$$
$$+ 13 \text{ m}^2 \times [7.47 \text{ kWh/m}^2 \times 0.67 - 0.00203 \text{ kW/(m}^2\cdot°\text{C)} \times 2.1°\text{C} \times 168 \text{ h}]$$
$$+ 16.5 \text{ m}^2 \times [7.47 \text{ kWh/m}^2 \times 0.5 - 0.00203 \text{ kWh/(m}^2\cdot°\text{C)} \times 2.1°\text{C} \times 168 \text{ h}] = 252.3 \text{ kWh} .$$

F.1.3 Trombe Wall (*TR*)

$$TR = Q_T \times A_T ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (0.28 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2).

$$TR = 0.28 \text{ kWh/m}^2 \times 12.3 \text{ m}^2 = 3.4 \text{ kWh} .$$

F.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 $kWh/(m^2 \cdot °C)$],
$CLTD_N$	=	adjusted cooling load temperature difference from ASHRAE Ch. 26, Table 7 (0.5°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004 \text{ kW/(m}^2\cdot°\text{C)} \times 0.5°\text{C} \times 22 \text{ m}^2 \times 168 \text{ h} = 0.7 \text{ kWh} .$$

F.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR \ ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2 \cdot$°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (5.7°C),
A_{EW}	=	east wall area (9.5 m^2).

$$W_E = 0.0004 \ \text{kWh/(m}^2\cdot{}^\circ\text{C)} \times 5.7^\circ\text{C} \times 9.5 \ \text{m}^2 \times 168 \ \text{h} = 3.6 \ \text{kWh} \ .$$

F.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR \ ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2 \cdot$°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (5.2°C),
A_{WW}	=	west wall area (25.3 m^2).

$$W_W = 0.0004 \ \text{kWh/(m}^2\cdot{}^\circ\text{C)} \times 5.2^\circ\text{C} \times 25.3 \ \text{m}^2 \times 168 \ \text{h} = 8.8 \ \text{kWh} \ .$$

F.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR \ ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.68 kWh/m^2),
CLF_E	=	cooling load factor (0.3),
A_E	=	east window area (0.56 m^2).

$$EW = 0.88 \times 0.68 \ \text{kWh/m}^2 \times 0.3 \times 0.56 \ \text{m}^2 \times 35 \ \text{h} = 3.5 \ \text{kWh} \ .$$

F.1.8 West Window (WW)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR \ ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_W$	=	maximum solar heat gain (0.51 kWh/m^2),
CLF_W	=	cooling load factor (0.3),
A_W	=	west window area (0.56 m^2).

$$WW = 0.88 \times 0.51 \text{ kWh/m}^2 \times 0.3 \times 0.56 \text{ m}^2 \times 35 \text{ h} = 2.6 \text{ kWh} \ .$$

F.1.9 Roof (R)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR \ ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation in the roof (-0.00022 kWh/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation in the roof (-0.00035 kWh/m^2),
A_R	=	roof area (372 m^2).

$$R = [0.5 \times (-0.00022 \text{ kWh/m}^2) + 0.5 \times (-0.00035 \text{ kWh/m}^2)] \times 372 \text{ m}^2 \times 168 \text{ h} = -17.8 \text{ kWh} \ .$$

F.1.10 Infiltration and ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7 \times HR_O + 0.5 \times HR_F) \ ,$$

where

ΔT	=	average temperature difference between inside and outside air (-1.0°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (145 h),
HR_F	=	hours with restroom exhaust fan off (23 h).

$$Q_{VI} = -1.0\text{°C} \times 0.343 \times 920 \text{ m}^3 \times (0.7 \times 145 \text{ h} + 0.5 \times 23 \text{ h}) = -35.7 \text{ kWh} \ .$$

F.2 BUILDING SENSIBLE THERMAL LOSSES

F.2.1 HEAT PUMP (Q_H)

$$Q_H = \sum_{i=1}^{HR} (Q_L) = -280 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by DAS each hour cooling is called for (kW).

F.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR \times CF_N ,$$

where

Q_{NW} = average inside heat flow sensor (-0.0017 kW/m^2),
A_W = bermed wall area (114 m^2),
CF_N = correction factor to account for more representative location of heat flow sensor on wall (1.0).

$$W_N = -0.0017 \text{ kW/m}^2 \times 114 \text{ m}^2 \times 168 \text{ h} \times 1.0 = -32.6 \text{ kWh} .$$

F.2.3 Floor (W_F)

$$W_F = Q_F \times A_F \times HR ,$$

where

Q_F = average heat flow from front and back floor sensors (-0.00125 kWh/m^2),
A_F = floor area (372 m^2).

$$W_F = -0.00125 \text{ kWh/m}^2 \times 372 \text{ m}^2 \times 168 \text{ h} = -78.1 \text{ kWh} .$$

F.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = 0 ,$$

where

Q_{HE} = amount of sensible cooling measured by DAS from economizer,

HR_E = hours in which the economizer damper is open.

Table F.1. Week 35 summary

Heat gains		Heat losses	
Source	kWh	Source	kWh
Internal loads	297.6	Heat pump	280.0
Windows		Bermed walls	32.6
South	252.1		
East	3.5	Floor	78.1
West	2.6		
Trombe	3.4	Economizer	0
Outside walls			
South	0.7		
East	3.6		
West	8.8		
Roof	−17.8		
Infiltration and ventilation	−35.7		
Total	518.8		390.7

Appendix G

ENERGY BALANCE FOR 1 h
(1400 on August 23, 1983)

G.1 BUILDING SENSIBLE THERMAL GAINS

$$G = IL + SW + TR + W_S + W_E + W_W + EW + WW + R + Q_{VI} , \quad (G.1)$$

where

G	=	building thermal gain,
IL	=	internal loads,
SW	=	south windows,
TR	=	trombe wall,
W_S	=	south wall,
W_E	=	east wall,
W_W	=	west wall,
EW	=	east window,
WW	=	west window,
R	=	roof,
Q_{VI}	=	infiltration and ventilation.

The terms are further explained in the following subsections.

G.1.1 Internal Loads (*IL*)

$$IL = \sum_{i=2}^{5} M_i - H_L - L_O + P_E - B_F - K_F + A_E , \quad (G.2)$$

where

M_i	=	submeters (in Eq. G.2, 0.836 kWh),
i	=	meter number (2 through 5 are for internal electric loads),
H_L	=	hot water energy lost through the drain as an estimated value using steady losses plus an additional 5% of the remaining energy use.

In Eq. G.2, $H_L = 0.95(M_2 - \Delta T_2 \times A_H \times U_H \times HR)$,

where

M_2	=	water heater meter reading for hour (0 kWh),
ΔT_2	=	temperature difference across water heater tank (35°C in summer),
A_H	=	water heater surface (3 m^2),
U_H	=	thermal transmittance of water heater wall [0.00081 kWh/($m^2 \cdot$°C)],
HR	=	hours (1 h),

$$H_L = 0.95[0 \text{ kWh} - 35°\text{C} \times 3 \text{ m}^2 \times 0.00081 \text{ kWh}/(\text{m}^2 \cdot °\text{C}) \times 1 \text{ h}] = -0.08 \text{ kWh} .$$

L_O (outside lights):

$$L_O = OL \times HR_D ,$$

where

OL	=	wattage of outside lights (0.44 kW),
HR_D	=	hours of darkness (0 h).

$$L_O = 0.44 \text{ kW} \times 0 \text{ h} = 0 \text{ kWh} .$$

P_E (sensible heat of occupants):

$$P_E = SH(BD \times HR_{BD} + OF) ,$$

where

SH	=	sensible heat per person per hour (0.073 kWh),
BD	=	number of beds occupied for energy balance period (0),
HR_{BD}	=	number of hours per day an overnight occupant spends in building (14 h),
OF	=	number of offices occupied for period of study (3).

$$P_E = 0.073 \text{ kWh} \times 3 = 0.22 \text{ kWh} .$$

B_F (restroom fan):

$$B_F = BP \times HR_O ,$$

where

BP = restroom fan power (0.2 kW),
HR_O = number of hours restroom exhaust fan is on (0 h).

$$B_F = 0.2 \text{ kW} \times 0 \text{ h} = 0 \text{ kWh} .$$

K_F (kitchen fan):

$$K_F = KF \times HR_K ,$$

where

KF = kitchen fan power (0.2 kW),
HR_K = length of time kitchen fan is on (0 h).

$$K_F = 0.2 \text{ kW} \times 0 \text{ h} = 0 \text{ kWh} .$$

A_E (data acquisition and fire alarm system power):

$$A_E = M_o - \sum_{i=1}^{5} M_i ,$$

where

M_o = master meter (1.3 kWh),
M_i = submeters (0.9 kWh).

$$A_E = (1.3 - 0.9) = 0.4 \text{ kWh} .$$

$$IL = 0.836 + 0.08 - 0 + 0.22 - 0 - 0 + 0.4 = 1.54 \text{ kWh} .$$

G.1.2 South-Facing Windows (SW)

$$SW = \sum_{i=1}^{3} A_i \times L_i \times SC_i ,$$

where

i	=	window location one through three,
A	=	window area (30, 13, 16.5 m^2),
L_i	=	pyranometer summation for period of study (0.175 kWh/m^2),
SC_i	=	average shading coefficient,
SC_1	=	0.75,
SC_2	=	0.67,
SC_3	=	0.5.

$$SW = 30 \text{ m}^2 \times 0.17 \text{ kWh/m}^2 \times 0.75 + 13 \text{ m}^2 \times 0.17 \text{ kWh/m}^3 \times 0.67 + 16.5 \text{ m}^2 \times 0.17 \text{ kWh/m}^2 \times 0.5 = 6.7 \text{ kWh} .$$

G.1.3 Trombe Wall (TR)

$$TR = Q_T \times A_T ,$$

where

Q_T	=	summation of hourly heat flow into building, as measured by inside heat flow sensor (0.007 kWh/m^2),
A_T	=	area of four trombe walls (12.3 m^2).

$$TR = 0.007 \text{ kWh/m}^2 \times 12.3 \text{ m}^2 = 0.086 \text{ kWh} .$$

G.1.4 South Wall (W_S)

$$W_S = U_{SW} \times CLTD_N \times A_{SW} \times HR ,$$

where

U_{SW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 $kWh/(m^2 \cdot °C)$],
$CLTD_N$	=	adjusted cooling load temperature difference from ASHRAE Ch. 26, Table 7 (8°C),
A_{SW}	=	south wall area (22 m^2).

$$W_S = 0.0004 \text{ kW/(m}^2 \cdot \text{°C)} \times 8\text{°C} \times 22 \text{ m}^2 \times 1 \text{ h} = 0.07 \text{ kWh} .$$

G.1.5 East Wall (W_E)

$$W_E = U_{EW} \times CLTD_E \times A_{EW} \times HR \ ,$$

where

U_{EW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2\cdot$°C)],
$CLTD_E$	=	adjusted cooling load temperature difference (12°C),
A_{EW}	=	east wall area (9.5 m^2).

$$W_E = 0.0004 \ \text{kWh/(m}^2\cdot\text{°C)} \times 12\text{°C} \times 9.5 \ \text{m}^2 \times 1 \ \text{h} = 0.0456 \ \text{kWh} \ .$$

G.1.6 West Wall (W_W)

$$W_W = U_{WW} \times CLTD_W \times A_{WW} \times HR \ ,$$

where

U_{WW}	=	thermal transmittance estimated from ASHRAE Ch. 23, 1981 [0.0004 kWh/(m$^2\cdot$°C)],
$CLTD_W$	=	adjusted cooling load temperature difference (10°C),
A_{WW}	=	west wall area (25.3 m^2).

$$W_W = 0.0004 \ \text{kWh/(m}^2\cdot\text{°C)} \times 10\text{°C} \times 25.3 \ \text{m}^2 \times 1 \ \text{h} = 0.1 \ \text{kWh} \ .$$

G.1.7 East Window (EW)

$$EW = SC_E \times MSHG_E \times CLF_E \times A_E \times HR \ ,$$

where

SC_E	=	shading coefficient (0.88),
$MSHG_E$	=	maximum solar heat gain (0.102 kWh/m^2),
CLF_E	=	cooling load factor (0),
A_E	=	east window area (0.56 m^2).

$$EW = 0.88 \times 0.102 \ \text{kWh/m}^2 \times 0.0 \times 0.56 \ \text{m}^2 \times 1 \ \text{h} = 0.0 \ \text{kWh} \ .$$

G.1.8 West Window (WW)

$$WW = SC_W \times MSGH_W \times CLF_W \times A_W \times HR ,$$

where

SC_W	=	shading coefficient (0.88),
$MSHG_W$	=	maximum solar heat gain (0.472 kWh/m^2),
CLF_W	=	cooling load factor (1.0),
A_W	=	west window area (0.56 m^2).

$$WW = 0.88 \times 0.472 \text{ kWh/m}^2 \times 1.0 \times 0.56 \text{ m}^2 \times 1 \text{ h} = 0.23 \text{ kWh} .$$

G.1.9 Roof (R)

$$R = (0.5 \times Q_{RB} + 0.5 \times Q_{RF}) \times A_R \times HR ,$$

where

Q_{RB}	=	heat flow through roof to north zone based on average temperature difference across insulation in the roof (0.0011 kWh/m^2),
Q_{RF}	=	heat flow through roof to south zone based on average temperature difference across insulation in the roof (0.0005 kWh/m^2),
A_R	=	roof area (372 m^2).

$$R = (0.5 \times 0.0011 \text{ kWh/m}^2 + 0.5 \times 0.0005 \text{ kWh/m}^2) \times 372 \text{ m}^2 \times 1 \text{ h} = 0.3 \text{ kWh} .$$

G.1.10 Infiltration and ventilation (Q_{VI})

$$Q_{VI} = \Delta T \times 0.343 \times V_C(0.7 \times HR_O + 0.5 \times HR_F) ,$$

where

ΔT	=	average temperature difference between inside and outside air (11°C),
V_C	=	building volume (920 m^3),
HR_O	=	hours with restroom exhaust fan on (0 h),
HR_F	=	hours with restroom exhaust fan off (1 h).

$$Q_{VI} = 11^\circ\text{C} \times 0.343 \times 920 \text{ m}^3 \times (0.7 \times 0 \text{ h} + 0.5 \times 1 \text{ h}) = 1.74 \text{ kWh} .$$

G.2 BUILDING SENSIBLE THERMAL LOSSES

G.2.1 Heat Pump (Q_H)

$$Q_H = \sum_{i=1}^{HR} (Q_L) = -6.6 \text{ kWh} ,$$

where

Q_L = heat pump output recorded by DAS each hour cooling is called for (kW).

G.2.2 Bermed Walls (W_N)

$$W_N = Q_{NW} \times A_W \times HR \times CF_N ,$$

where

Q_{NW} = average inside heat flow sensor (-0.002 kW/m^2),
A_W = bermed wall area (114 m^2),
CF_N = correction factor to account for more representative location of heat flow sensor on wall (1.0).

$$W_N = -0.002 \text{ kW/m}^2 \times 114 \text{ m}^2 \times 1 \text{ h} \times 1 = -0.23 \text{ kWh} .$$

G.2.3 Floor (W_F)

$$W_F = Q_F \times A_F \times HR ,$$

where

Q_F = average heat flow from front and back floor sensors (0.001 kWh/m^2),
A_F = floor area (372 m^2).

$$W_F = -0.001 \text{ kWh/m}^2 \times 372 \text{ m}^2 \times 1 \text{ h} = -0.372 \text{ kWh} .$$

G.2.4 Economizer (Q_E)

$$Q_E = \sum_{i=1}^{HR_E} Q_{HE} = 0 ,$$

where

Q_{HE}	=	amount of sensible cooling measured by DAS from economizer,
HR_E	=	hours in which the economizer damper is open.

Table G.1. Summary for hour 1400, August 23, 1983

Heat gains		Heat losses	
Source	kWh	Source	kWh
Internal loads	1.54	Heat pump	6.6
Windows		Bermed walls	0.23
South	6.7		
East	0.0	Floor	0.37
West	0.23		
Trombe	0.09	Economizer	0.0
Outside walls			
South	0.07		
East	0.05		
West	0.1		
Roof	0.3		
Infiltration and ventilation	1.73		
Total	10.8		7.2

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